

JADE Analysis in the New Millenium

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UCLA Experimental Particle and Nuclear
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David J. Gross

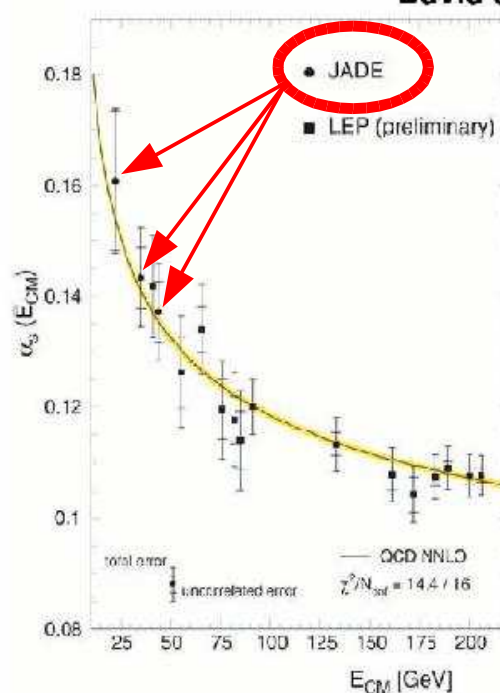
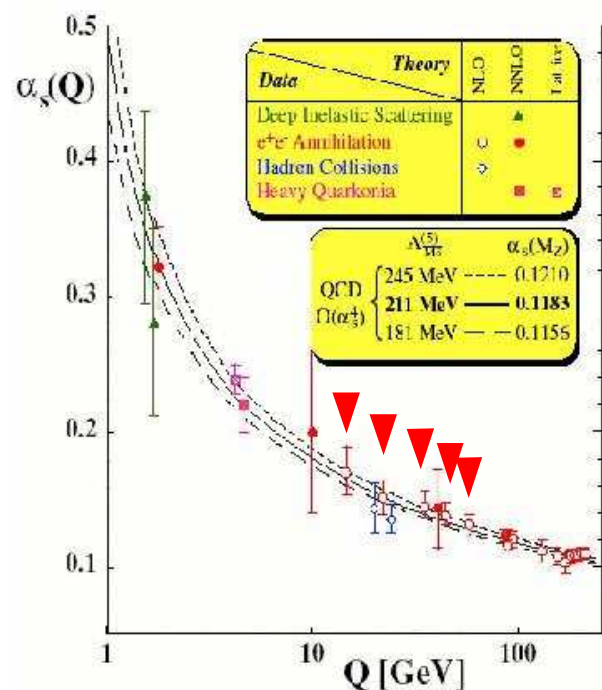


H. David Politzer



Frank Wilczek

Asymptotic Freedom and Quantum Chromodynamics: the Key to the Understanding of the Strong Nuclear Forces



...taken from the
Physics Nobel Prize
press release
(Oct 5, 2004)

The left-hand panel shows a collection of different measurements by S. Bethke from High-Energy International Conference in Quantum Chromodynamics, Montpellier 2002 (hep-ex/0211012). The right-hand panel shows a collection by P. Zerwas, Eur. Phys. J. C34(2004)4. **JADE was one of the experiments at PETRA at DESY.** NNLO means Next-to-Next-to-Leading Order computation in QCD.

<http://nobelprize.org/physics/laureates/2004/press.html>

Outline

- Motivation
- The Experiment
- Resurrection of Data and Software
- Recent QCD results
 - ▶ α_s from event topologies and jet rates
(includes recent OPAL results)
 - ▶ Power corrections
 - ▶ QCD color structure
- Summary and Conclusions

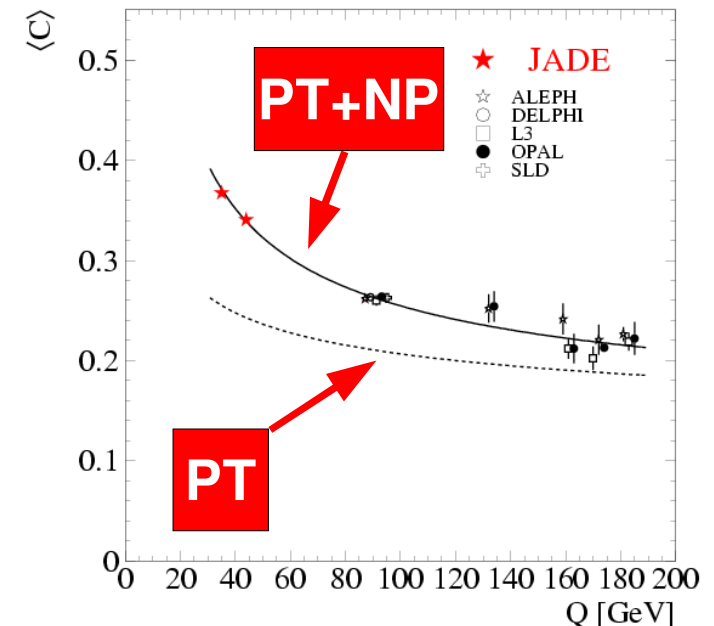
Motivation

**JADE analysis probes QCD
at low energy scales Q
with state-of-the-art techniques**

- large leverage for predictions:

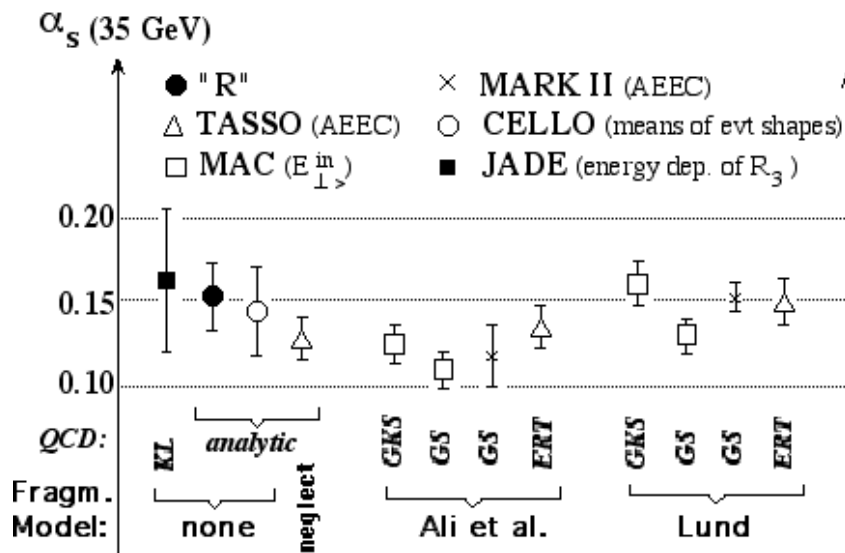
**PT effects $\propto 1/\log(Q)$
NP effects $\propto 1/Q$ (event shapes)**

- interplay between hard and soft QCD
best studied at “medium” energies
- JADE provides unique contribution for the energy range 14-44 GeV
 - ▶ ~1500 ... 35000 multihadronic events/energy point,
precise energy bins
- LEP FSR- Z^0 analysis technique
 - ▶ $O(500-1000)$ events/energy point down to $\sqrt{s}=40$ GeV,
coarse energy bins



α_s at PETRA Times

- 1973 Concept of asymptotic freedom
- 1979 Discovery of the gluon at PETRA
- 1979 MARK-J Coll.: First direct measurement α_s using LO for oblateness
- 1979+ $\alpha_s = 0.15 \dots 0.23$ @ $\sqrt{s} = 30$ GeV based on LO predictions
- 1982 CELLO Coll., JADE Coll.: First “significant” measurements of α_s based on NLO for thrust and differential 3-jet cross section
- 1982+ $\alpha_s(35\text{GeV}) = 0.11 \dots 0.19$ based on NLO predictions



- ...inconsistent results due to
- incomplete NLO matrix elements
- obsolete MC models

Summary value 1989:
 $\alpha_s(35\text{GeV}) = 0.14 \pm 0.02$

What's happened since PETRA

- LEP/SLC learned from QCD
PETRA/PEP experiences, now PETRA
in turn profits from LEP
- QCD predictions have drastically
improved since PETRA shutdown
 - ▶ Development of new event shape
variables with better theoretical
properties (e.g. infrared safe), also new
jet finders
 - ▶ New theoretical perturbative predictions,
e.g. resummed NLO calculations for
event shapes
 - ▶ New/improved hadronization models
(Pythia, Herwig, Ariadne)
 - ▶ Novel analytical approach to describe
hadronization (power corrections)
 - ▶ ...

PETRA/PEP 1980's



**QCD input for
LEP/SLC**

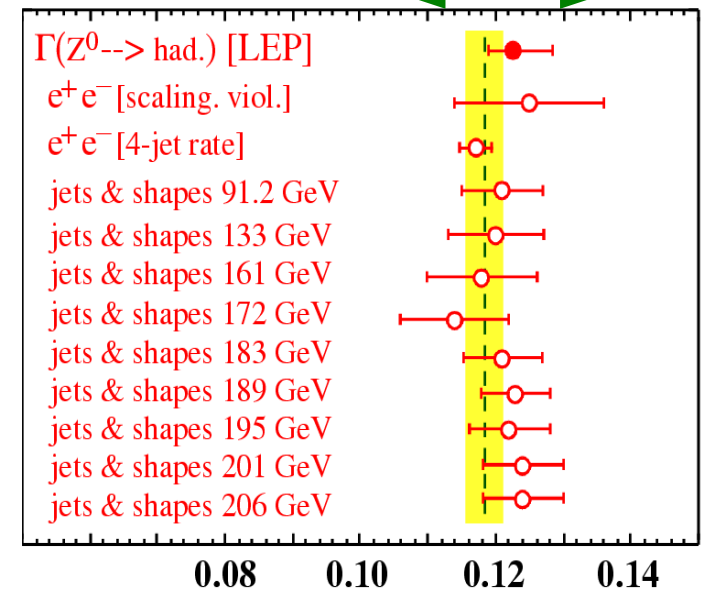
LEP/SLC



**feedback for
PETRA**

PETRA 2000

$\alpha_s(M_Z)$ 1989



S.Bethke: hepex/040721

Nucl.Phys.Proc.Suppl.135 (2004) 345

$\alpha_s(M_Z)$

The JADE Revival Group

- RWTH Aachen, MPI Munich, DESY
S. Bethke, O. Biebel, M. Blumenstengel, S. Kluth,
P.A.M.F., C. Pahl, P. Pfeifenschneider, J. Schieck and J.E. Olsson
- Since 1998: 25+ publications/conference contributions based on/involving the reanalysed JADE data
- New JADE results have been considered in numerous publications from LEP collaborations / QCD theory groups

Eur. Phys. J. C **1**, 461-478 (1998)

THE EUROPEAN
PHYSICAL JOURNAL C
© Springer-Verlag 1998

A study of event shapes and determinations of α_s using data of e^+e^- annihilations at $\sqrt{s} = 22$ to 44 GeV

P.A. Movilla Fernández¹, O. Biebel¹, S. Bethke¹, S. Kluth², P. Pfeifenschneider¹, the JADE Collaboration

27 September 2001

PHYSICS LETTERS B

JADE Note 146
MPP-2001-99
August 6, 2004

Physics Letters B **517** (2001) 37-46

www.elsevier.com/locate/npe



Measurement of the longitudinal and transverse cross-section in e^+e^- annihilation at $\sqrt{s} = 35-44$ GeV

M. Blumenstengel, O. Biebel, P.A. Movilla Fernández, P. Pfeifenschneider¹,
S. Bethke, S. Kluth

JADE Collaboration

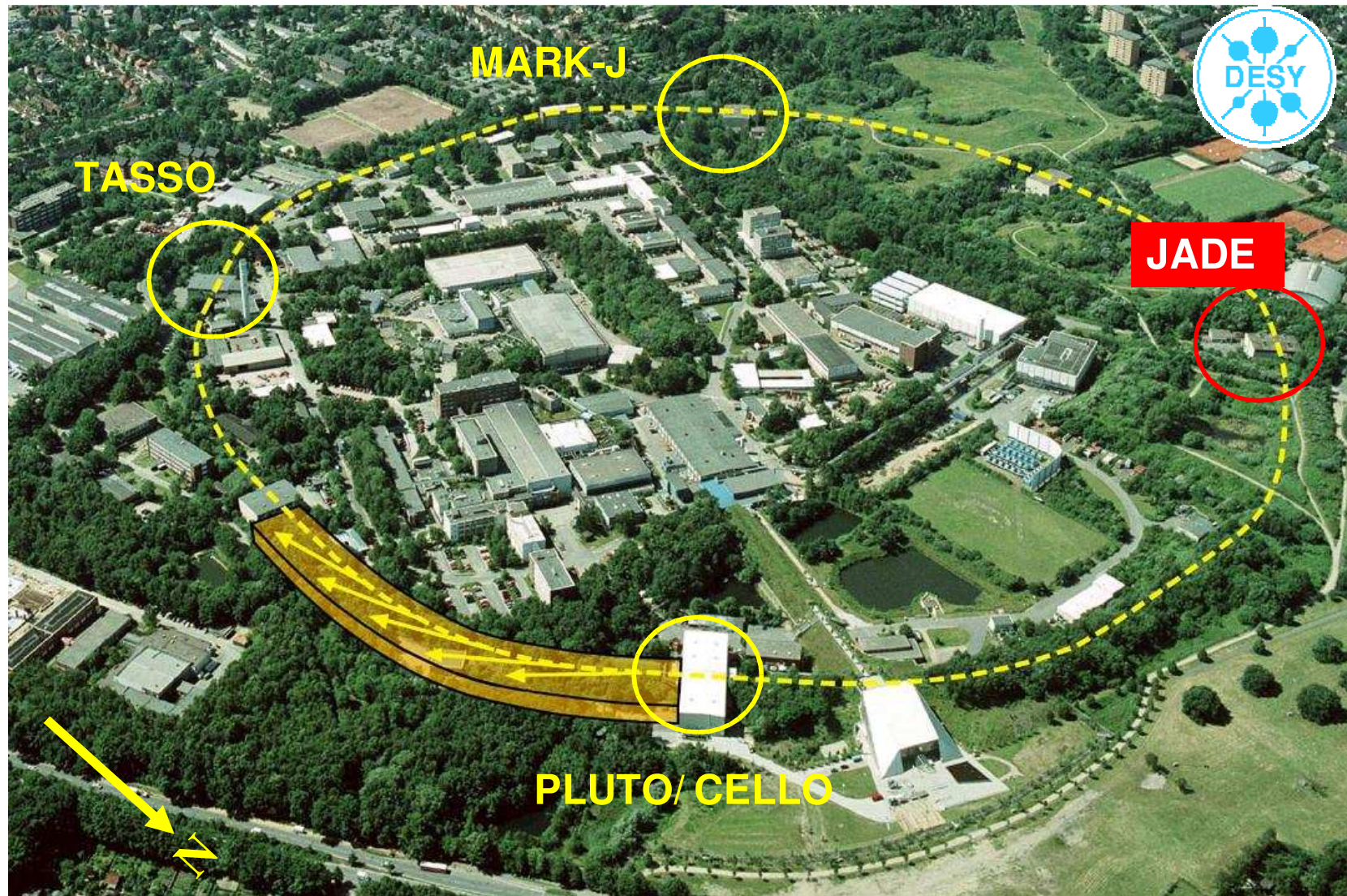
Measurement of the Strong Coupling Constant α_s from the Four-Jet Rate in e^+e^- Annihilation using JADE data

J. Schieck, S. Kluth, S. Bethke, P.A. Movilla Fernández, C. Pahl,
and the JADE Collaboration

The Experiment



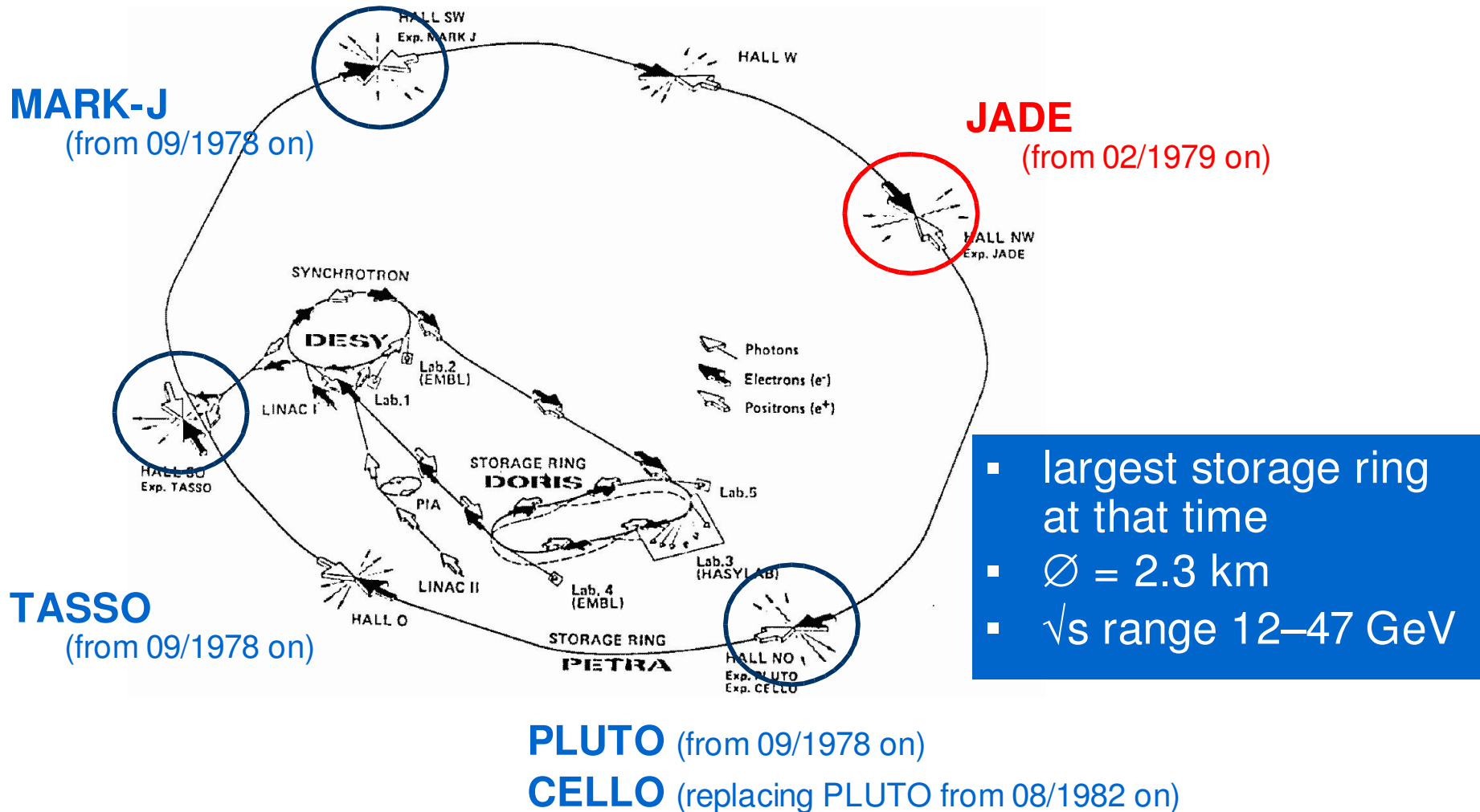
The PETRA e^+e^- Storage Ring



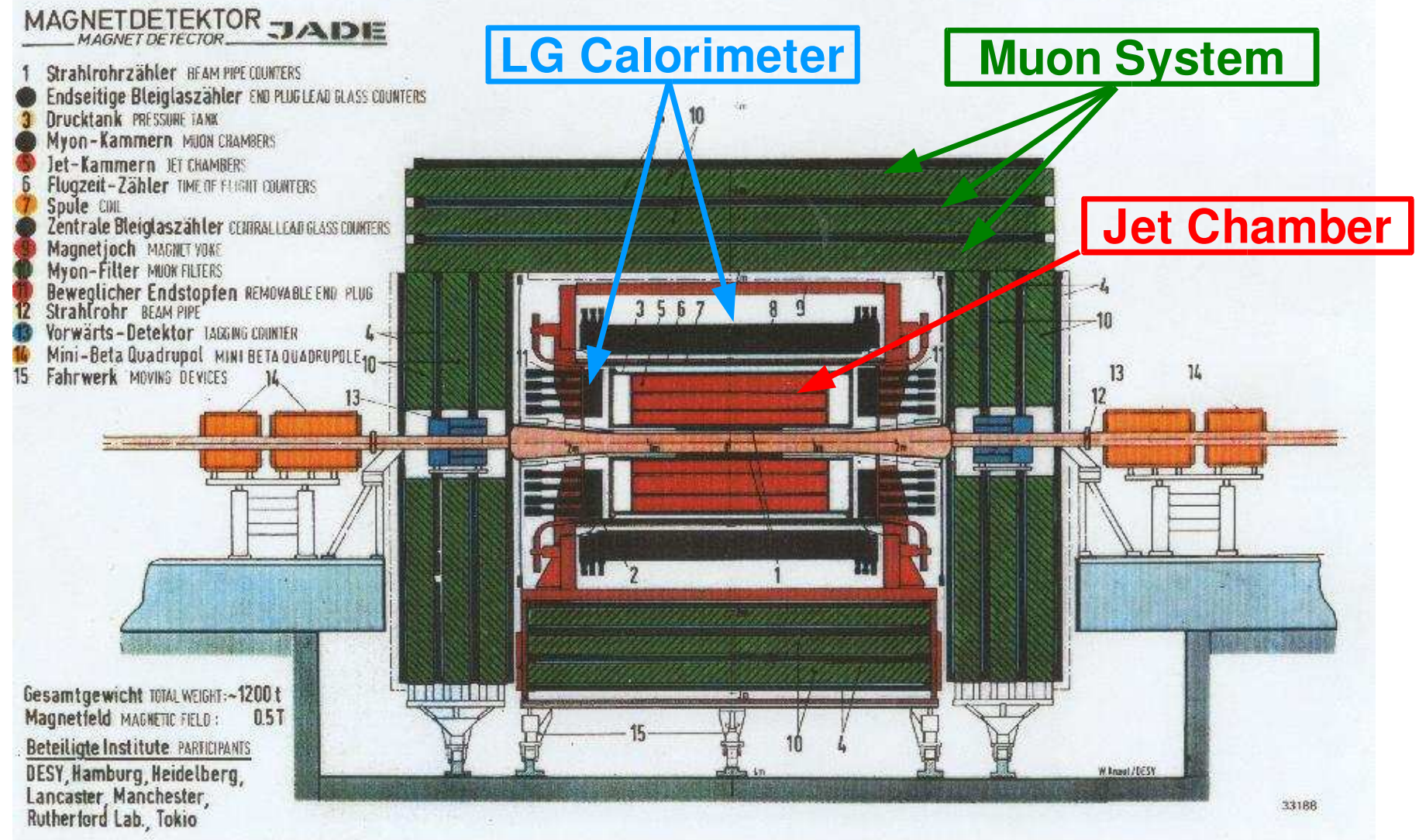
DESY, Hamburg

The PETRA e^+e^- Storage Ring

Operated 1978-1986 at DESY, Hamburg

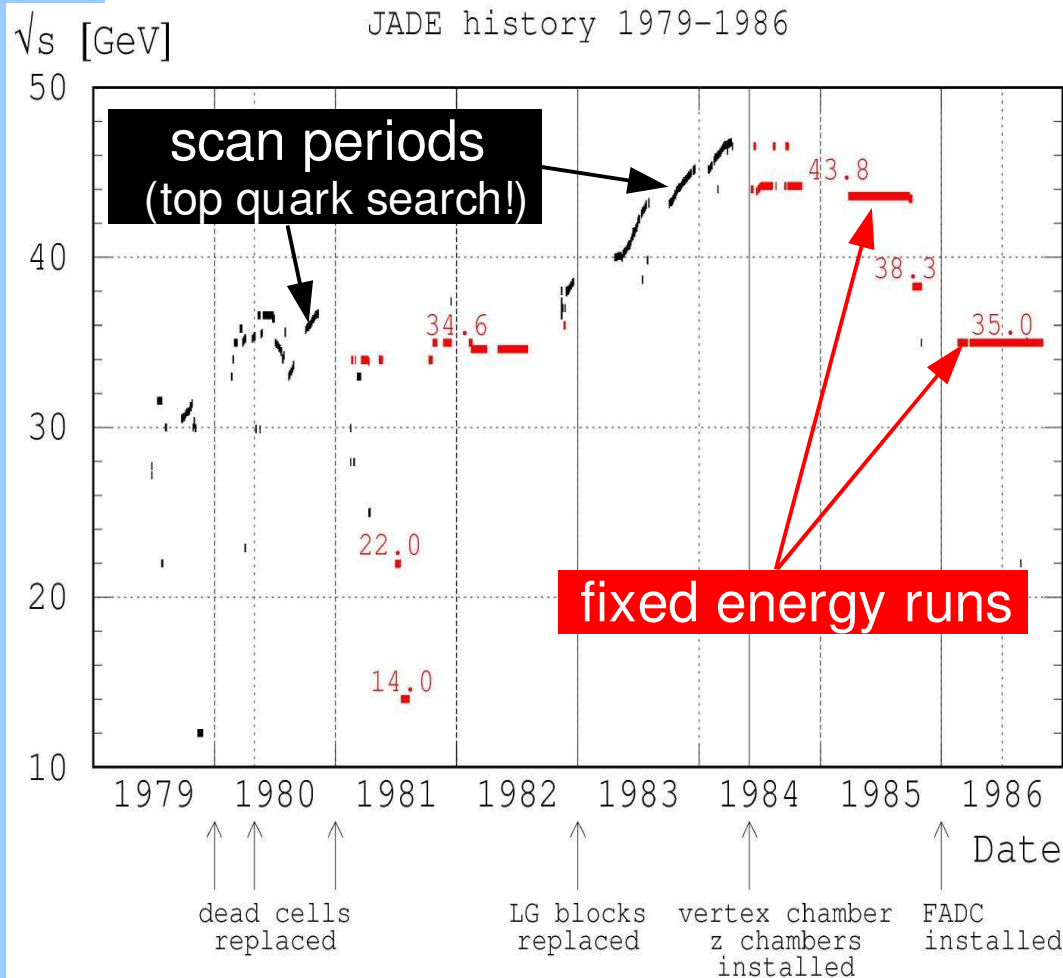


The JADE Detector

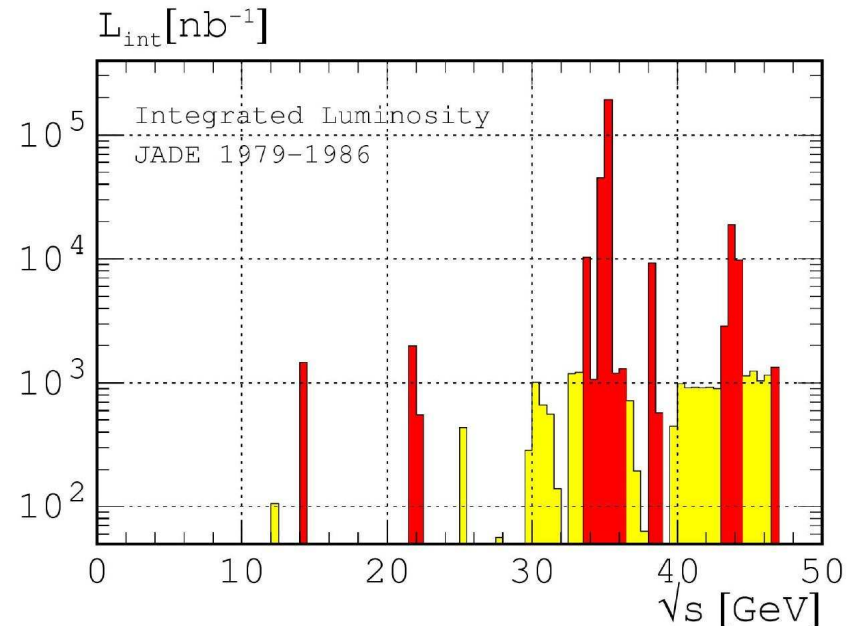


120 collaborators from **J**Apan (Tokyo), **D**eutschland (DESY, Hamburg, Heidelberg), **E**ngland (Lancaster, Manchester, RAL), USA (Maryland)

C.M.S. Energies and Luminosities



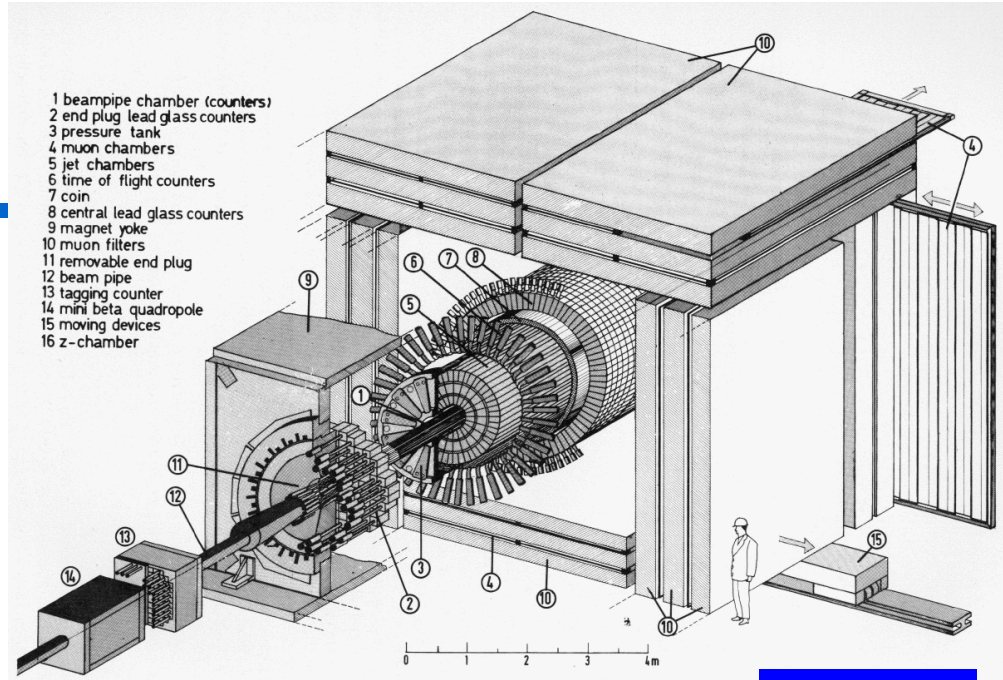
various detector upgrades



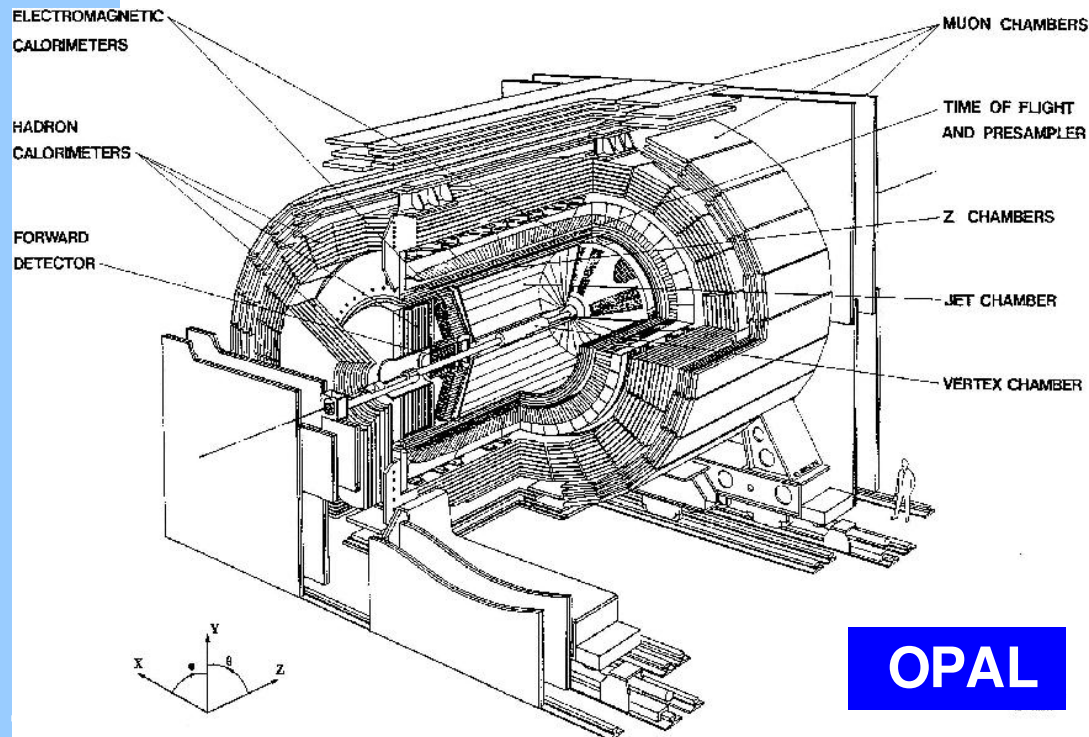
- 216 pb⁻¹ total integrated luminosity collected by JADE
- Peak luminosity: 24 $\mu b^{-1}s^{-1}$
⇒ 26 multihadrons per hour
@ $\sigma^{had}=0.3$ nb
- ≈ 43000 “clean” multihadrons

JADE ...

- **Inner Detector:** Magnetic field ($\sim 0.5\text{T}$), pictorial drift chamber, vertex chamber, Z chamber, TOF
- **EM Calorimeter:** lead glass blocks, barrel+endcaps
- **Muon Detector:** drift chamber / absorber layers
- No hadron calorimeter



JADE



OPAL

... & OPAL

Concept very similar
(Jet Chamber, LG Calorimeter)

- operated 1989 – 2000 at LEP
- \sqrt{s} range 91...209 GeV
- collected $O(10^6)$ multihadronic events

JADE Resurrection



Recovery of JADE Data ...

- Original data were located at
 - ▶ IBM mainframe at the DESY computer center
 - ▶ IBM tapes at DESY and Heidelberg U.
- **DESY IBM closed completely in July 1997**
 - ▶ **last-minute transfer** to “modern” data carriers (IBM/EXABYTE cartridges) and computer platforms
- Data organized by “antique” data management system **BOS** (version 1979)
- Raw data (REDUC1/REDUC2) converted into FPACK format (platform independent)
- Multihadronic data sets (ZE4V ~ “mini-DST”) converted into ASCII format → **used for current analyses**

Recovery of the JADE Data

However, not all information were available in electronic format...

...convert it to electronic version by hand

JADE luminosity files

RUNS		BEAM	BARREL	LUMINOSITY
13856	13864	20.840	0.474029E+02 +-	0.779300E+01
13865	13872	20.855	0.538850E+02 +-	0.831464E+01
13873	13885	20.870	0.719484E+02 +-	0.961450E+01
13886	13895	20.885	0.694769E+02 +-	0.945461E+01
13896	13906	20.900	0.579792E+02 +-	0.864303E+01
13907	13919	20.915	0.516098E+02 +-	0.816022E+01
13920	13931	20.930	0.555588E+02 +-	0.847264E+01
13932	13941	20.945	0.465800E+02 +-	0.776333E+01
13942	13953	20.960	0.285056E+02 +-	0.607743E+01
13954	13963	20.975	0.609841E+02 +-	0.889545E+01
13964	13973	20.990	0.519744E+02 +-	0.821787E+01
13974	13980	21.005	0.442404E+02 +-	0.758717E+01
13981	13989	21.020	0.508176E+02 +-	0.813734E+01
13990	13998	21.035	0.678519E+02 +-	0.940937E+01
13999	14009	21.050	0.770938E+02 +-	0.100368E+02
14011	14021	21.065	0.667339E+02 +-	0.934461E+01
14022	14031	21.080	0.497930E+02 +-	0.807749E+01
14032	14043	21.095	0.524870E+02 +-	0.829892E+01
14044	14054	21.110	0.499324E+02 +-	0.810010E+01
14055	14065	21.125	0.667388E+02 +-	0.777265E+01

- Also preprocessed JADE detector simulation samples (ZE4V) available, but:
 - ▶ not for all relevant energy points (only 35 and 44 GeV)
 - ▶ older generators
 - ▶ simulation parameters not well documented
- For more/better MC samples reactivation of JADE software necessary!

Revival of the JADE Software

Programs:

- **Detector simulation**
detailed particle tracking, detector response, inefficiencies, resolution
- **Event analysis software**
pattern recognition, cluster analysis ...
- **JADE interactive graphics**
event display, event analysis, event editing
- **Multihadronic event filtering and packing software**

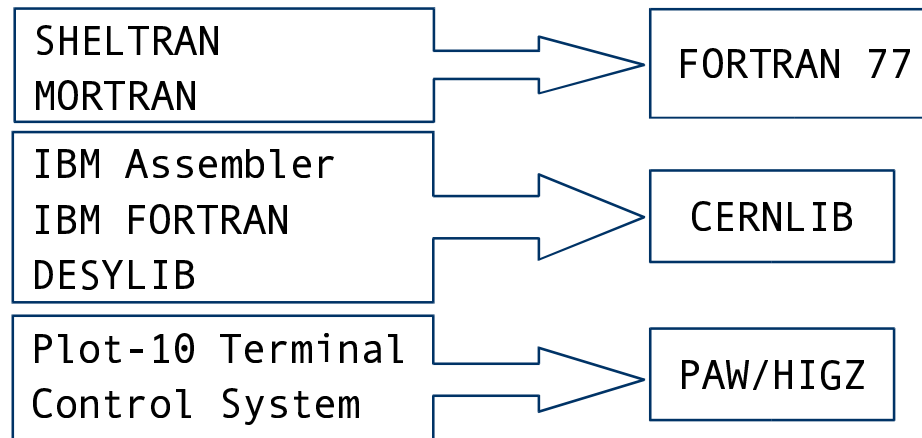
Source code:

- Code fragments from 1974
- Mixture of different FORTRAN standards (FORTRAN IV, FORTRAN 77)
- “Illegal” IBM specific extensions
- Ancient pre-compiler code (SHELTRAN, MORTRAN)
- IBM/370 assembler code

...extremely unstructured, badly documented “spaghetti” code

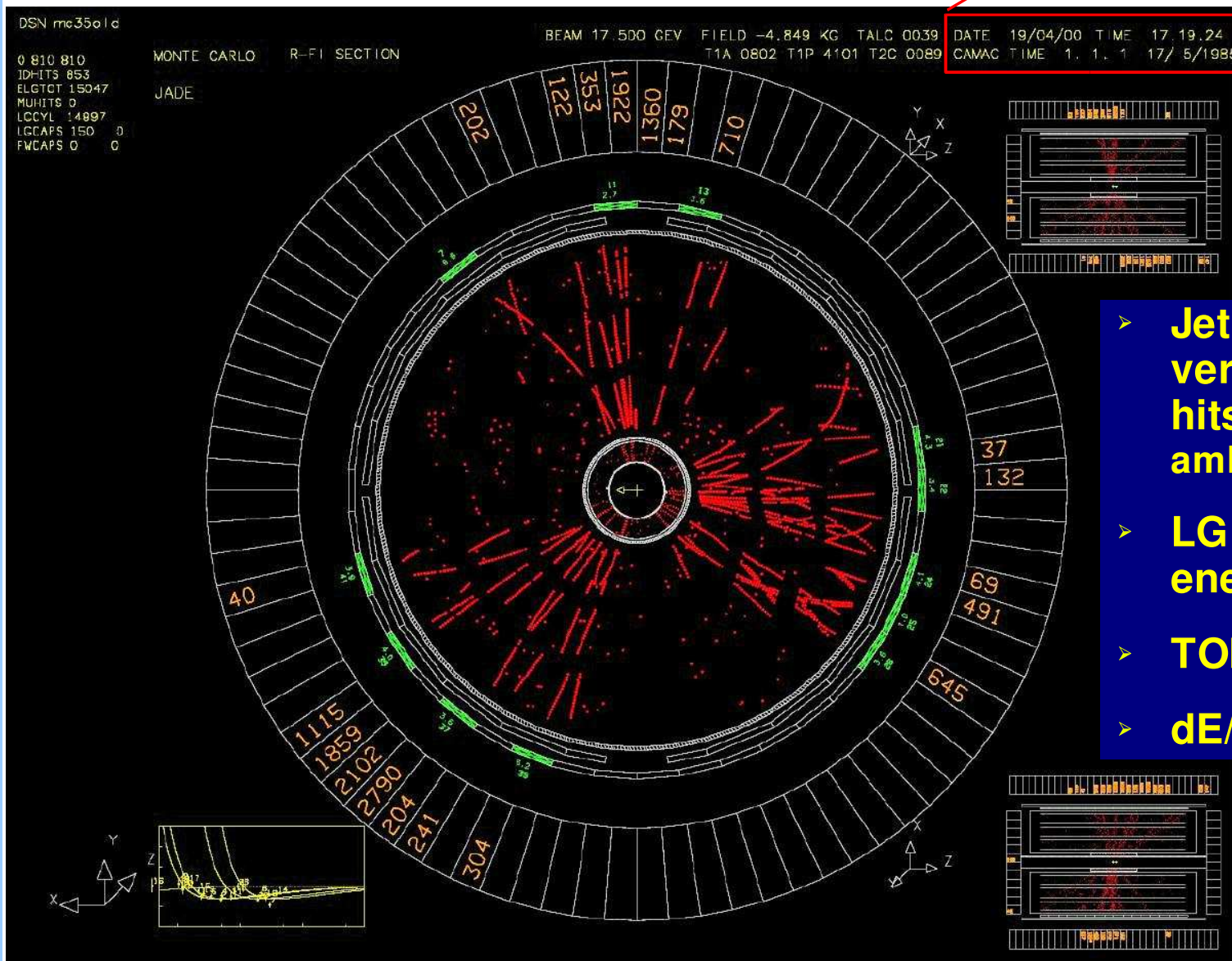
Revival of the JADE Software

- “Historical/archaeological” research work using old JADE notes, PhD theses, manual fragments, source code comments.
- Code modification, emulation interfaces for missing libraries (e.g. graphics), obsolete FORTRAN dialects, etc.



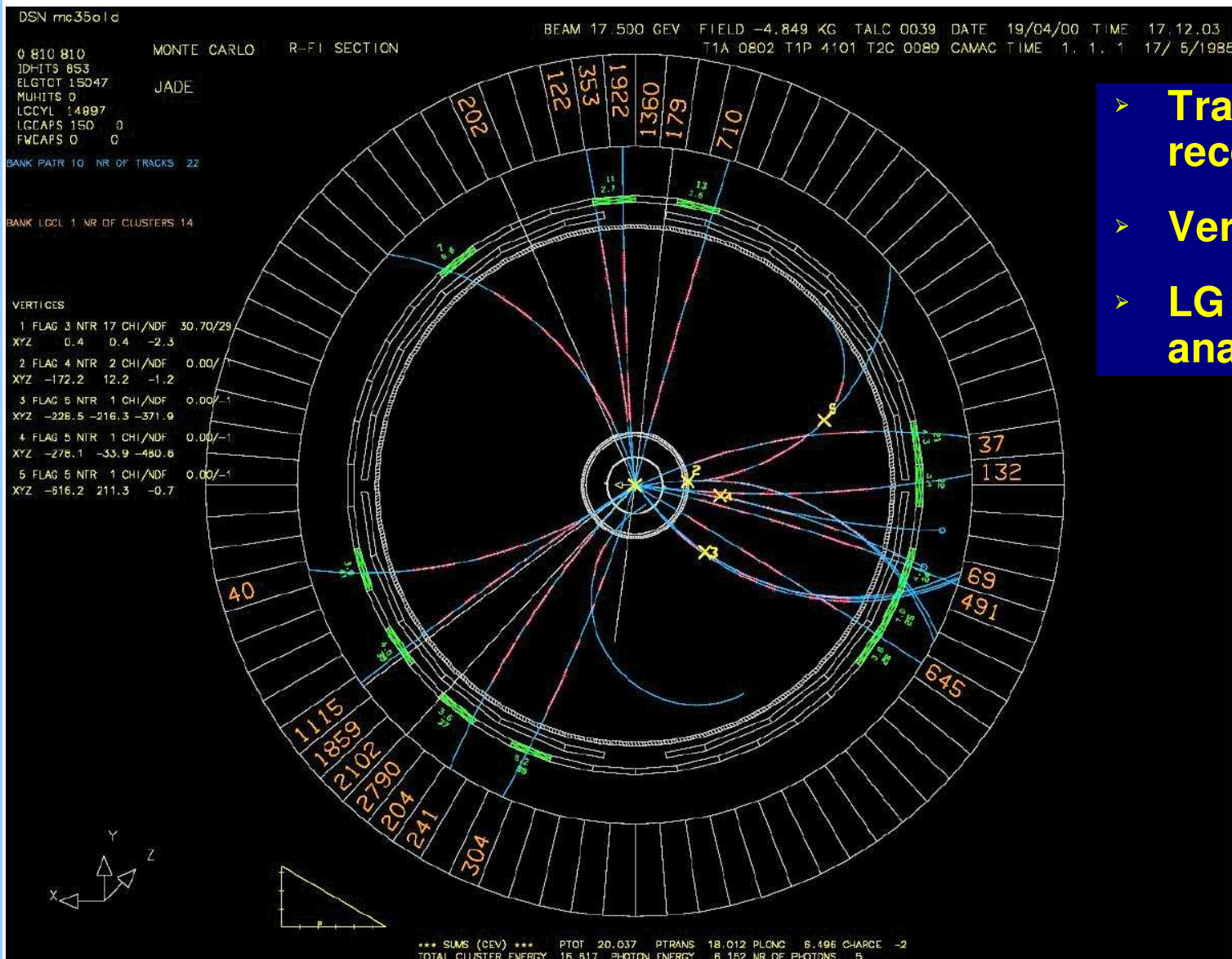
- Platform dependencies extremely problematic
 - ▶ Bit/byte manipulation of data words
 - ▶ Access to BOS banks not in units of a fixed word length (4 bytes)
 - ▶ Byte storage order (IBM is big endian, PC is little endian)
- Complete installation successful on IBM RS/6000 AIX (same endian scheme as IBM/370) with XLF compiler.

JADE Event Display



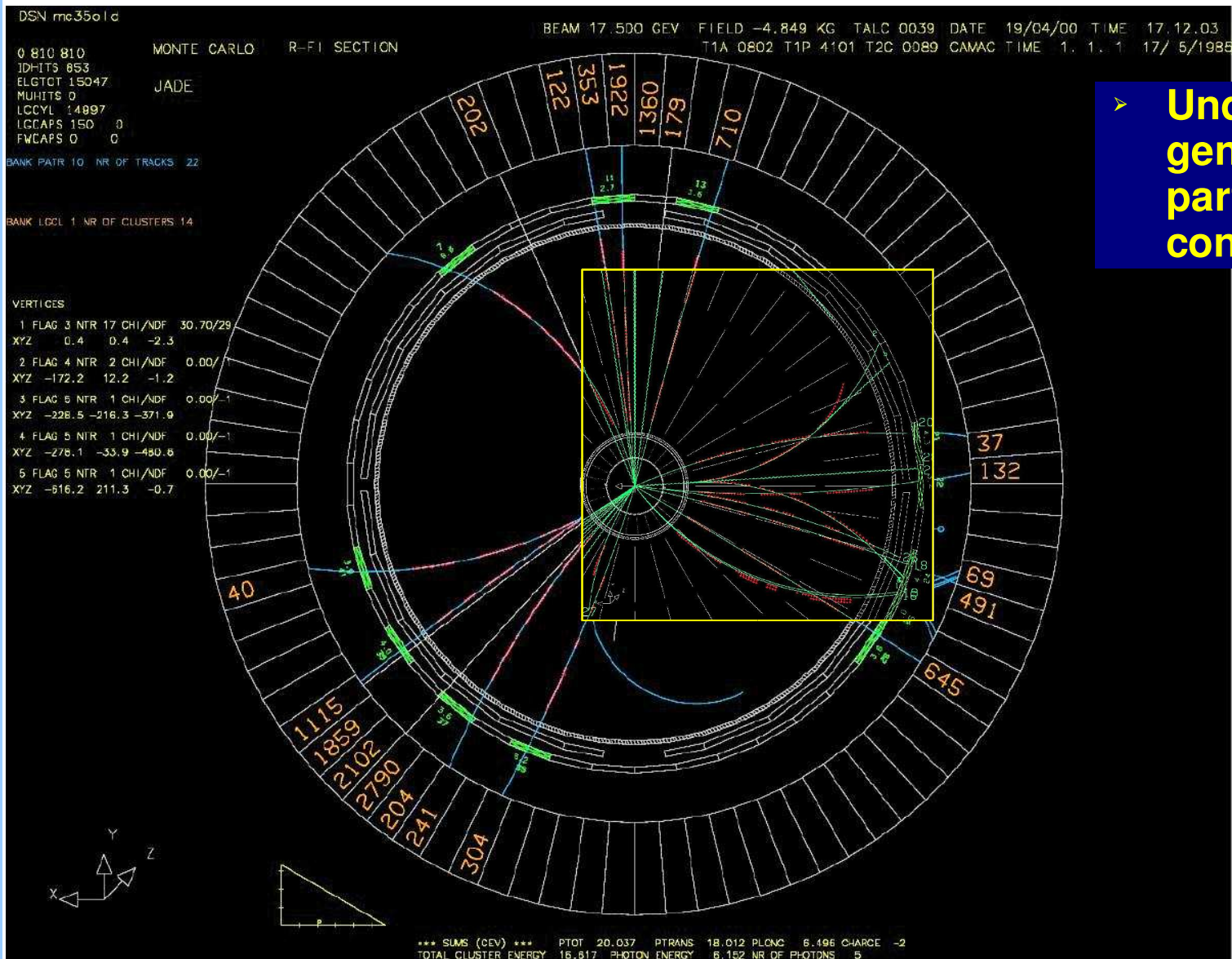
- Jet chamber / vertex chamber hits (incl. R/L ambiguities)
- LG calorimeter energies
- TOF hits
- dE/dx meas.

JADE Event Display



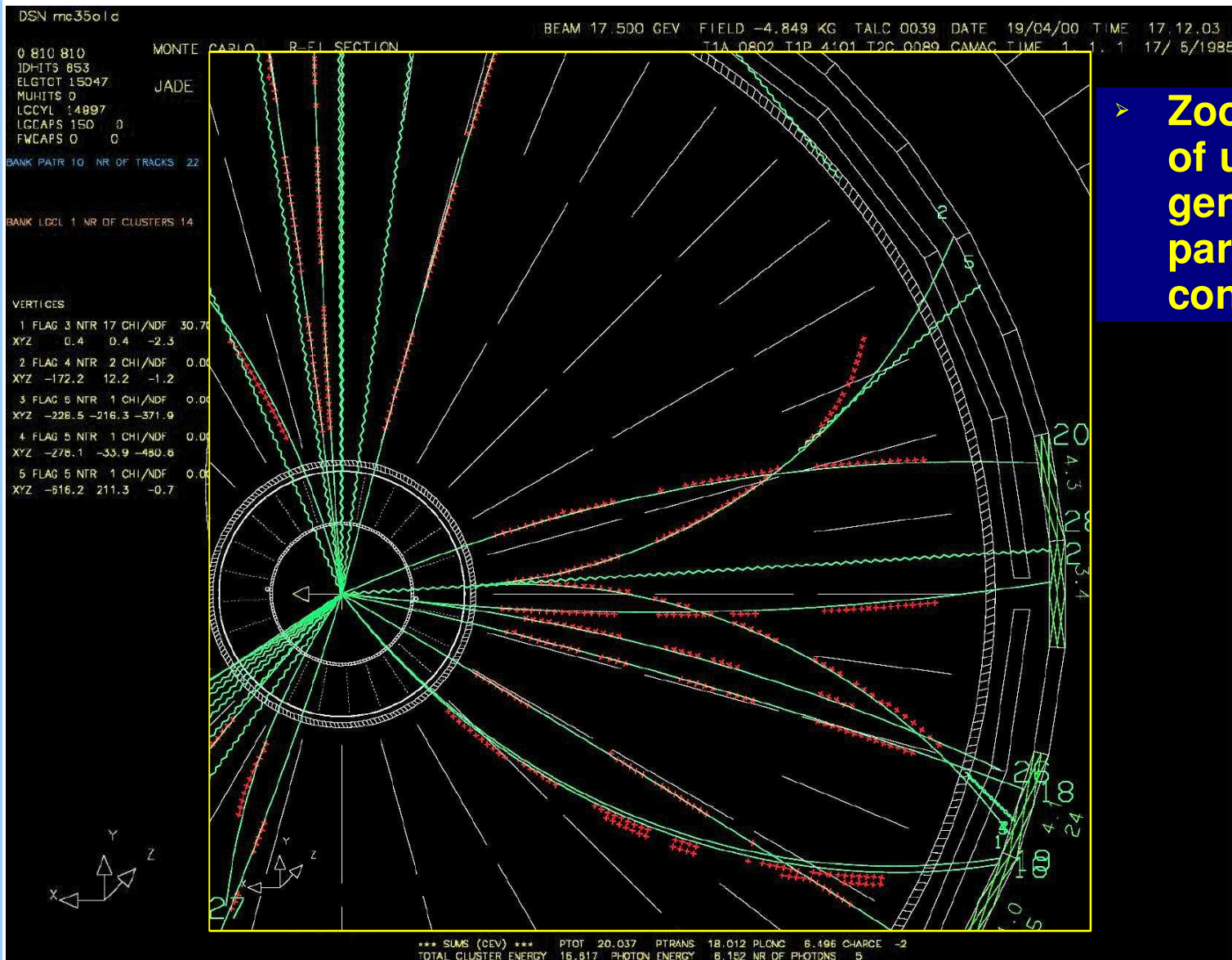
- Track reconstruction
- Vertex finding
- LG cluster analysis

JADE Event Display



➤ Underlying generated particle configuration

JADE Event Display



➤ Zoomed section of underlying generated particle configuration

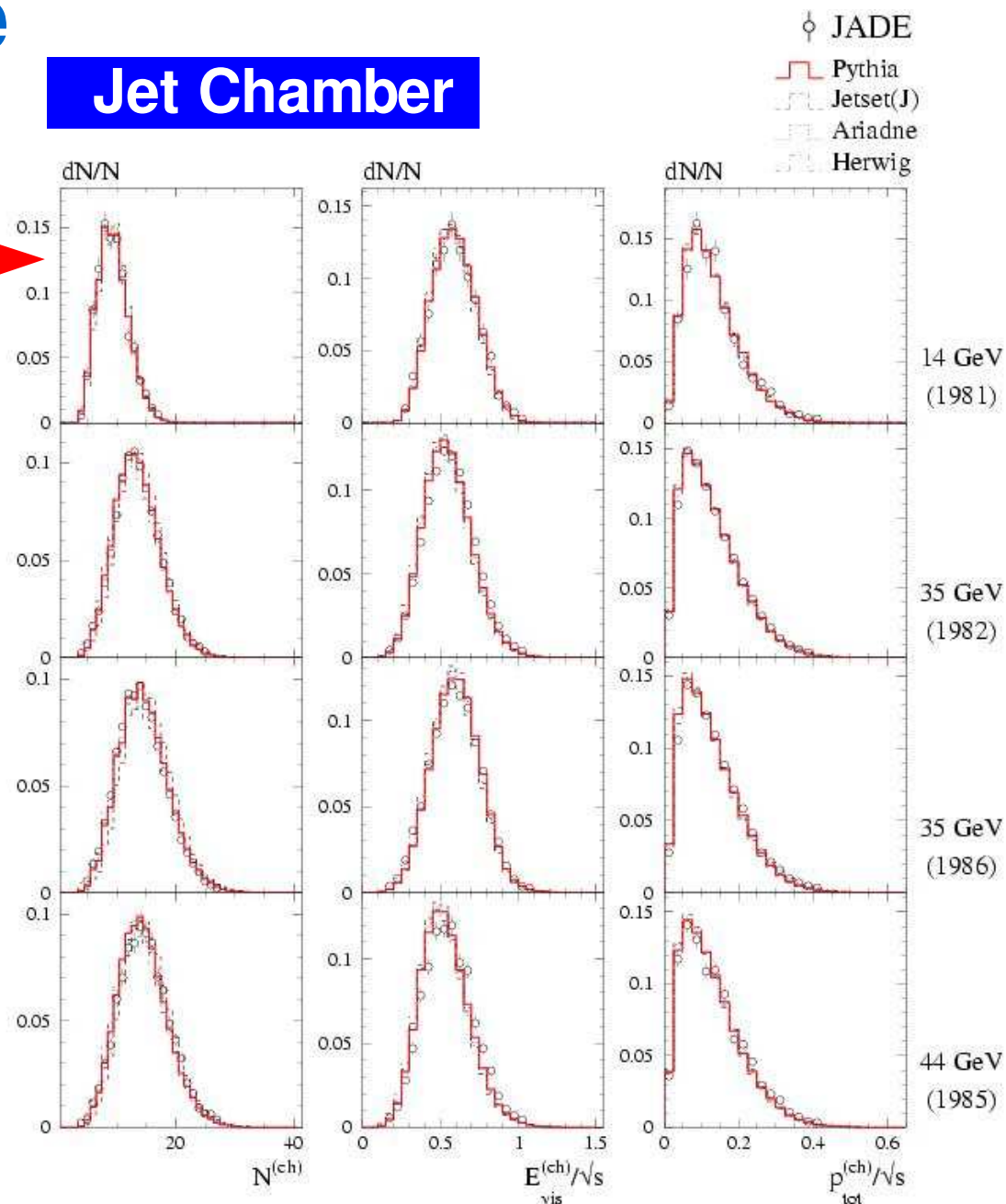
Performance

Jet Chamber

Example:

$$N^{(ch)}, E_{vis}^{(ch)}/\sqrt{s}, p_{tot}^{(ch)}/\sqrt{s}$$

- JADE simulation with OPAL LEP-I tuned event generator
- generally good description of data from 14-44 GeV

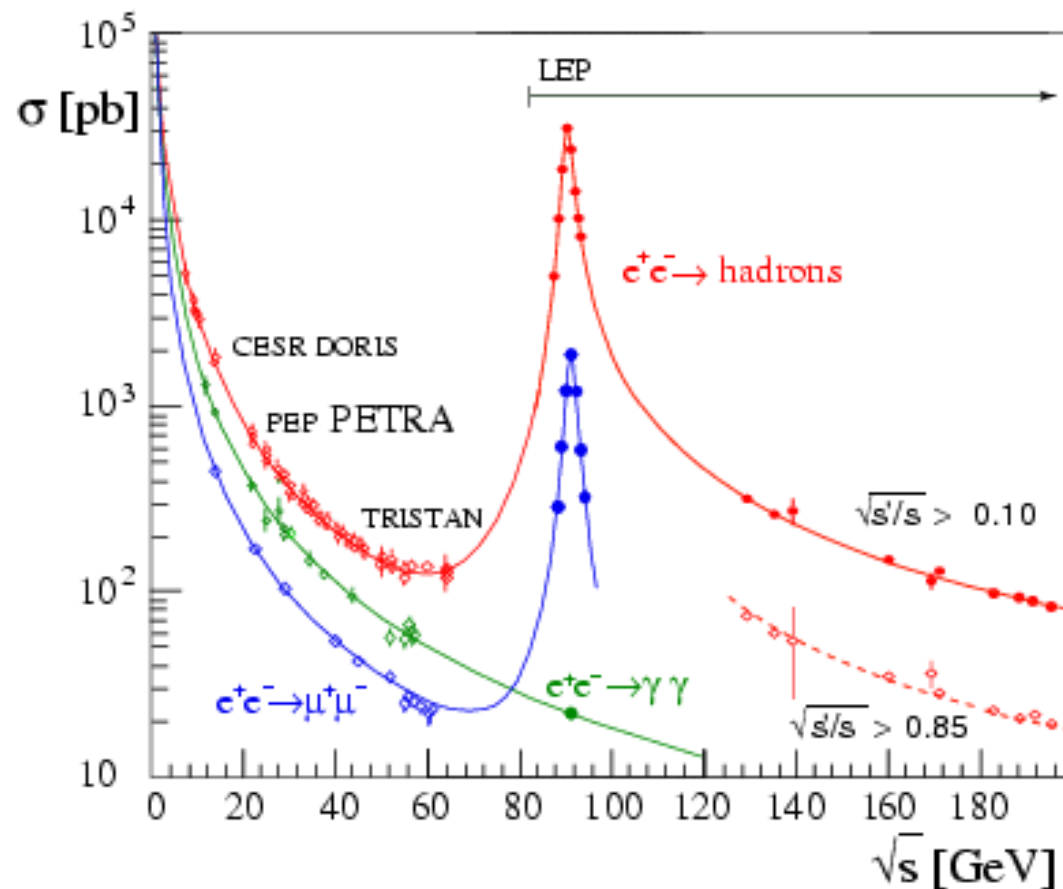


Event Shapes in e^+e^- Annihilation



Hadronic Final States

Cross section for $e^+e^- \rightarrow \text{hadrons}$

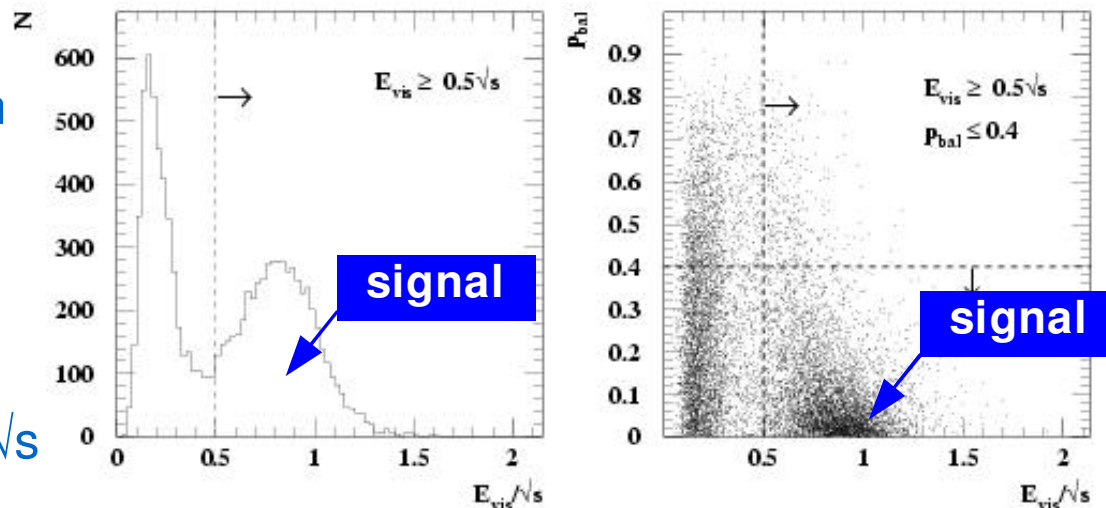


- $\sigma^{\text{had}}(\text{PETRA}) = 0.2 \dots 3\text{nb} \approx 1/10 \dots 1/100 \sigma^{\text{had}}(\text{LEP I})$
- Hadron production at PETRA energies mainly via $e^+e^- \rightarrow \gamma^* \rightarrow q\bar{q}(g)$

Multihadronic Data Sets

Main selection cuts:

- 4 tracks from vertex region
- 3 “long + good” tracks
- **visible energy $> 0.5 \cdot \sqrt{s}$**
- **momentum balance**
 $|\Sigma p_z|/E_{\text{vis}} < 0.4$
- missing momentum $< 0.3 \cdot \sqrt{s}$
- $|\cos \Theta_{\text{Thrust}}| < 0.8$



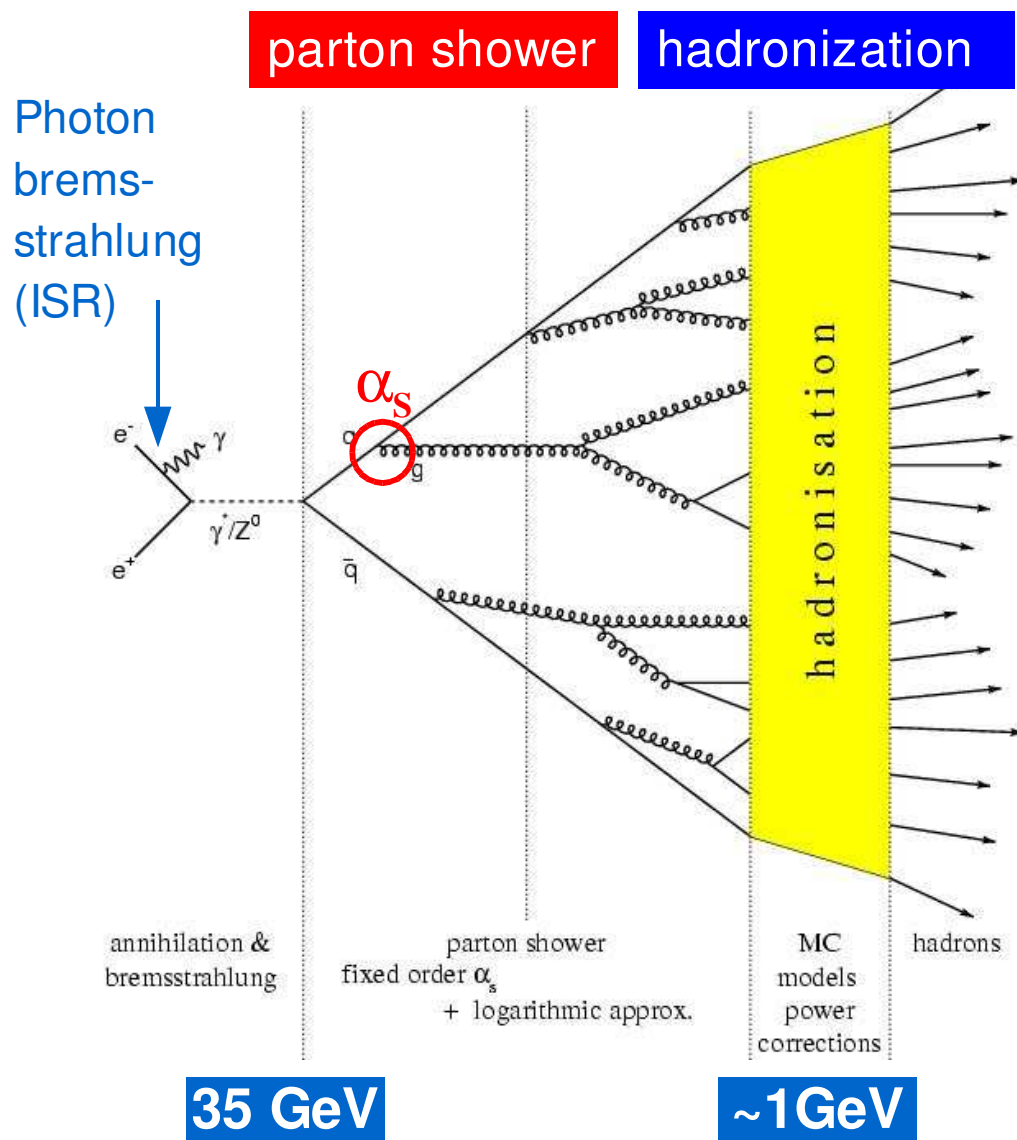
Very clean samples,
residual background $\approx 1\%$:

- $e^+e^- \rightarrow e^+e^- \gamma\gamma$
- $e^+e^- \rightarrow \tau^+ \tau^-$

MH data samples

\sqrt{s} -range [GeV]	data taking period	\mathcal{L} [pb^{-1}]	$\langle \sqrt{s} \rangle$ [GeV]	MH data
14.0	Jul.-Aug. 1981	1.46	14.0	1734
22.0	Jun.-Jul. 1981	2.41	22.0	1390
33.8 – 36.0	Feb. 1981 - Aug. 1982	61.7	34.6	14372
35.0	Feb.-Nov. 1986	92.3	35.0	20925
38.3	Oct.-Nov. 1981	8.28	38.3	1587
43.4 – 46.6	Jun. 1984 - Oct. 1985	28.8	43.8	3940

QCD in e^+e^- Annihilation



Various theoretical approaches to describe parts of the process:

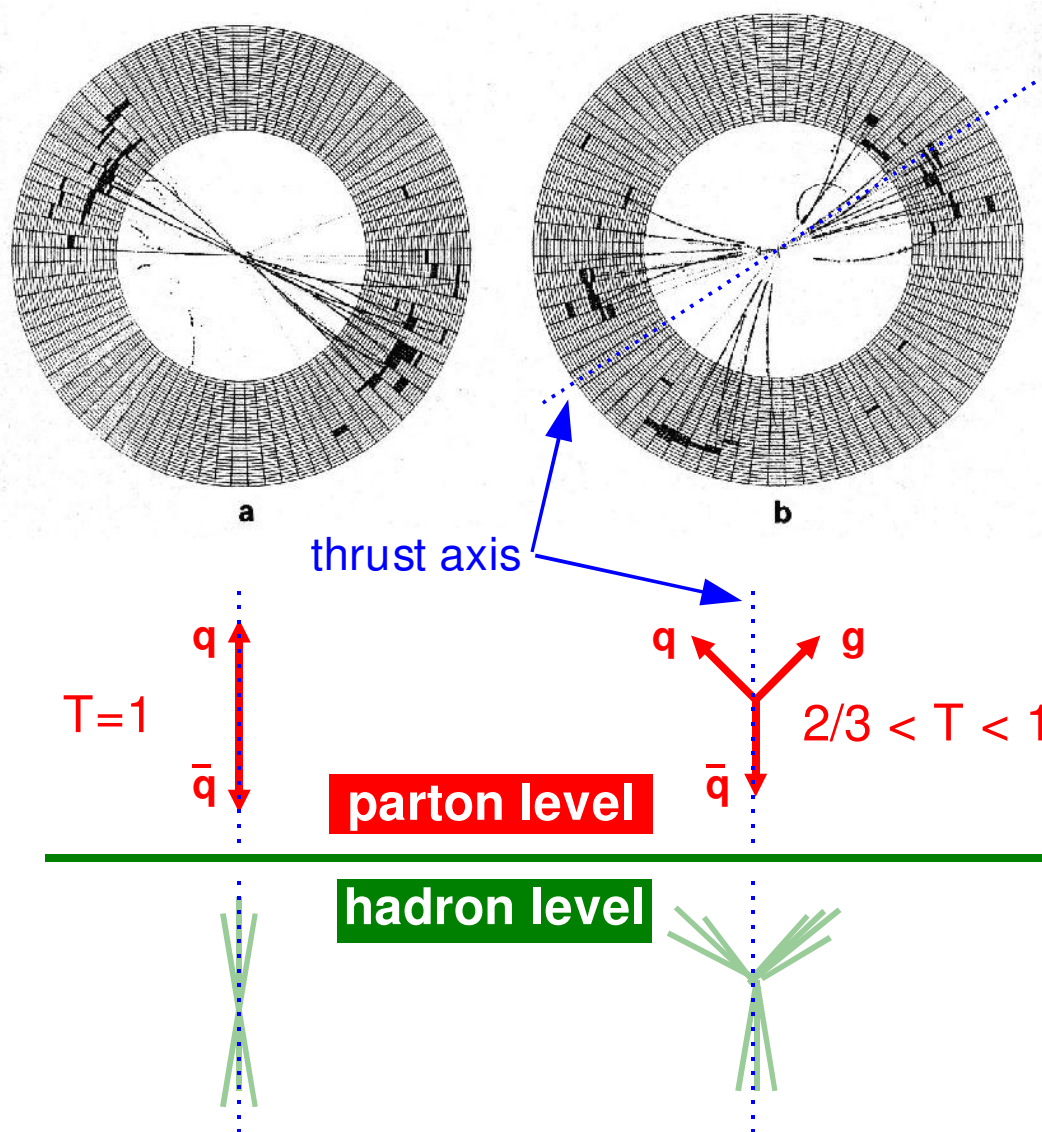
PT QCD:

- $O(\alpha_s^2)$, NLLA, ...
- Parton shower MC

NP QCD:

- Phenomenological hadronization models: **string fragmentation**, **cluster model**
- Analytical power corrections

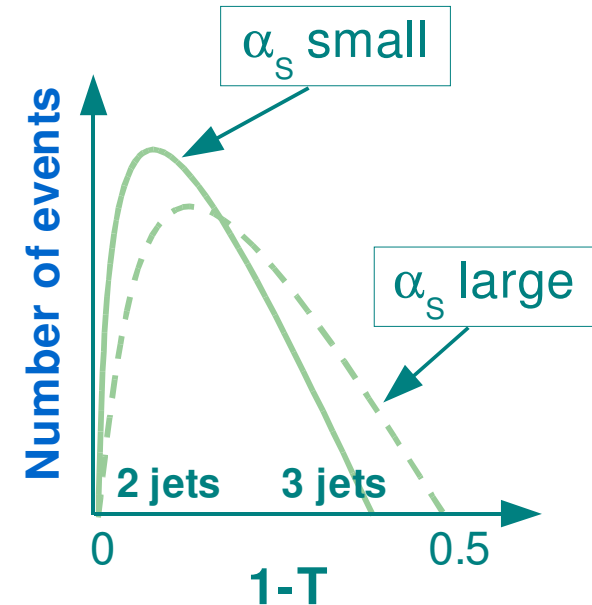
Hadronic Event Shapes



Quantify the event topology by a single number.

Example: “**Thrust**”

$$T = \max_{\vec{n}} \left(\frac{\sum_i |\vec{p}_i \cdot \vec{n}|}{\sum_i |\vec{p}_i|} \right)$$



Event shape variables are important tools to probe PT and NP effects.

More Event Shapes ...

Thrust T

$$T = \max_{\vec{n}} \left(\frac{\sum_i |\vec{p}_i \vec{n}|}{\sum_i |\vec{p}_i|} \right)$$

...defines two hemispheres

H_k

$$M_k^2 = \left\{ \left(\sum_i E_i \right)^2 - \left(\sum_i \vec{p}_i \right)^2 \right\}_{i \in H_k}$$

hemisphere masses

$$B_k = \frac{\sum_{i \in H_k} |\vec{p}_i \times \vec{n}_T|}{2 \sum_i |\vec{p}_i|}, \quad k = 1, 2$$

hemisphere p_T

Heavy Jet Mass M_H

$$M_H^2 = \frac{\max(M_1^2, M_2^2)}{(\sum_i E_i)^2}$$

Total / Wide Jet Broadening B_T, B_W

$$B_T = B_1 + B_2$$

$$B_W = \max(B_1, B_2)$$

C Parameter

$$\Theta^{\alpha\beta} = \frac{\sum_i (p_i^\alpha p_i^\beta) / |\vec{p}_i|}{\sum_i |\vec{p}_i|}, \quad \alpha, \beta = 1, 2, 3$$

$$C = 3(\lambda_1 \lambda_2 + \lambda_2 \lambda_3 + \lambda_3 \lambda_1)$$

= $3 \langle \sin^2 \theta_{ij} \rangle$: average of the momentum weighted angle between pairs of particles

- Calculate eigenvalues λ_i from linearised momentum tensor.

Differential 2-jet rate y_{23} (Durham scheme)

$$y_{ij} = \frac{2 \min(E_i^2, E_j^2) (1 - \cos \theta_{ij})}{(\sum_k E_k)^2}$$

$$\frac{dR_2(y_{\text{cut}})}{dy_{\text{cut}}} = \frac{1}{\sigma} \frac{d\sigma(y_{23})}{dy_{23}}$$

- Define jet resolution parameter y_{ij} .
- Combine particles i, j with smallest y_{ij} into pseudo particles and proceed until $y_{ij} > y_{\text{cut}}$ for 2 remaining pseudo particles ("jets").

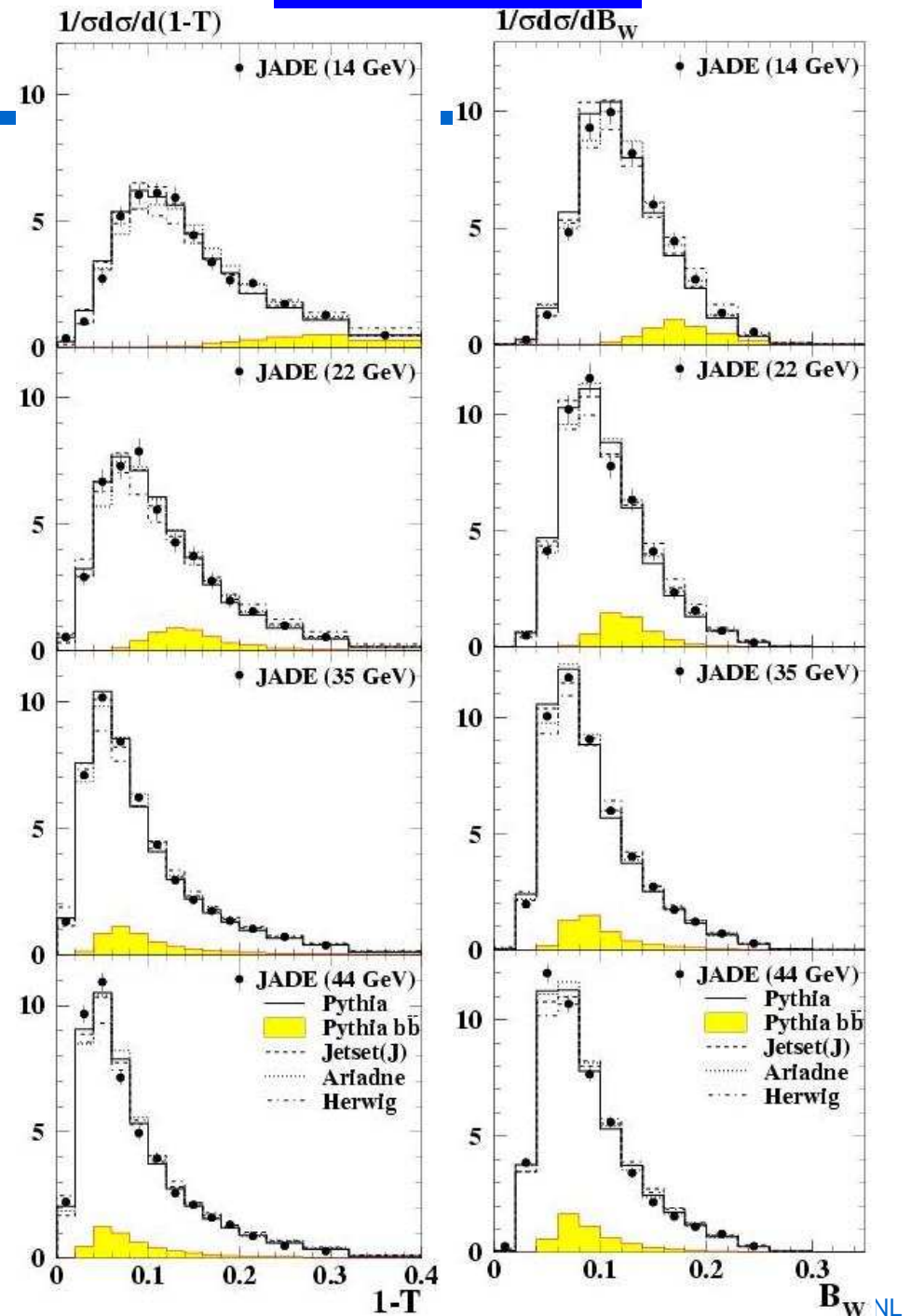
y_{23} is value of y_{cut} for which event switches from 3 jet to 2 jet type

MC Models

- **PYTHIA/JETSET**
LLA parton shower +
string fragmentation
- **ARIADNE**
colour dipole scheme +
string fragmentation
- **HERWIG**
MLLA parton shower +
cluster fragmentation
- **COJETS**
LLA parton shower +
independent fragmentation

**Monte Carlo +
JADE simulation reproduce
multihadronic data!**

detector level

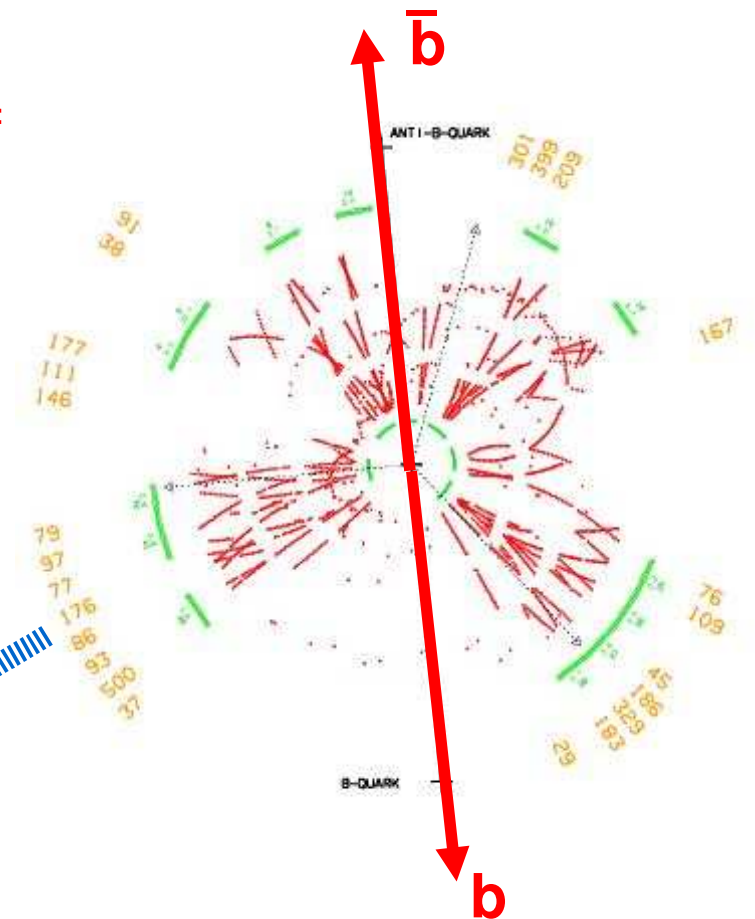
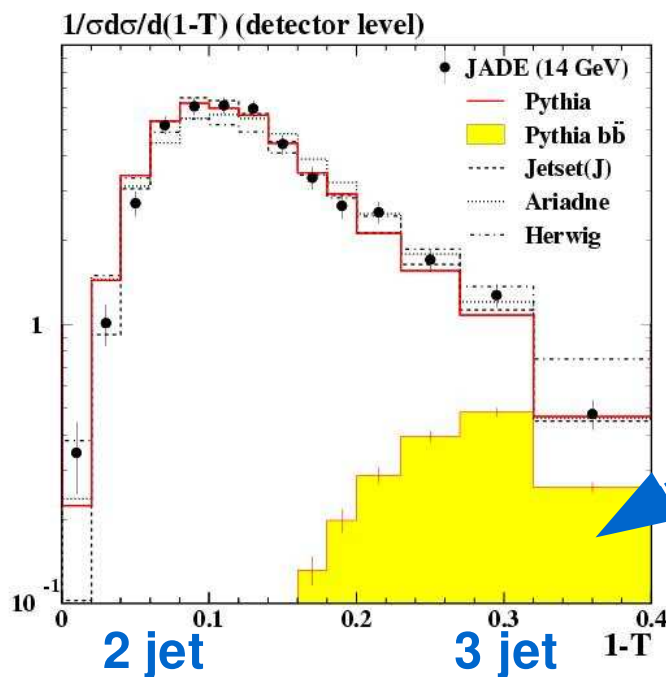


Correction Procedure (1)

$b\bar{b}$ subtraction at detector level

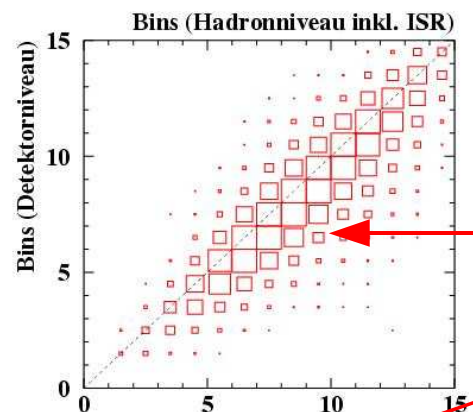
- about 9% fraction of hadronic final states
- fakes hard gluon radiation due to electroweak decays + mass effects
... treated as “background” in view of later comparison with “massless” QCD calculations

Pythia $e^+e^- \rightarrow b\bar{b}$, 14 GeV



Correction Procedure (2)

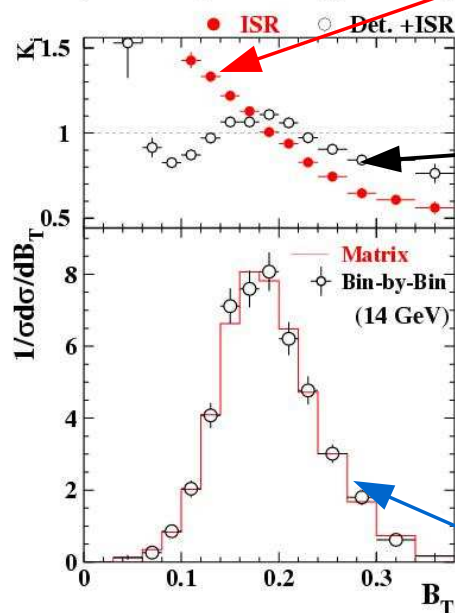
- Detector effects, MH selection
limited resolution, acceptance effects, secondary processes
- Photon ISR



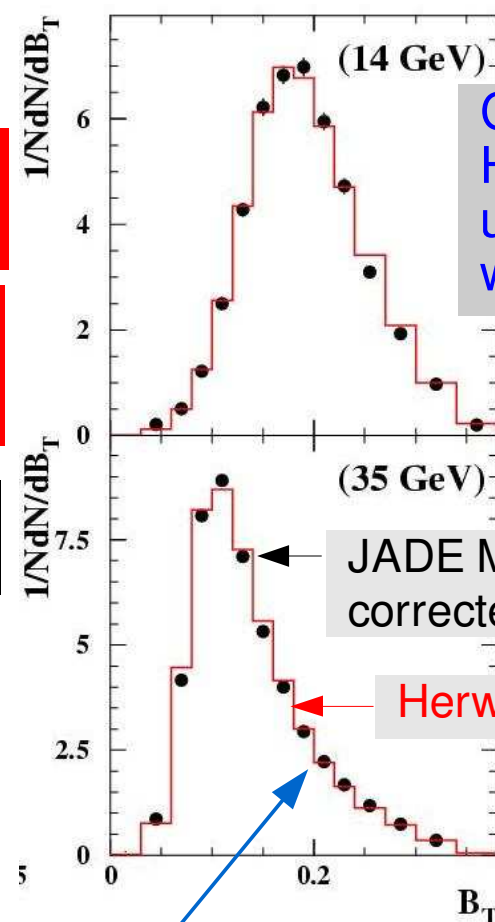
pure detector effects
(matrix correction)

ISR correction
(partially compensated by
detector effects)

total bin-by-bin
correction



consistent “hadron levels”



Check:
Herwig MC
unfolded
with Pythia

JADE MC (Herwig)
corrected

Herwig hadrons

“Physics” Data

Comparison with MC models:
PYTHIA (LEP I tune)

- good overall consistency

HERWIG/ARIADNE

- moderate at 14+22 GeV, better at higher \sqrt{s}

JETSET (JADE optimization)

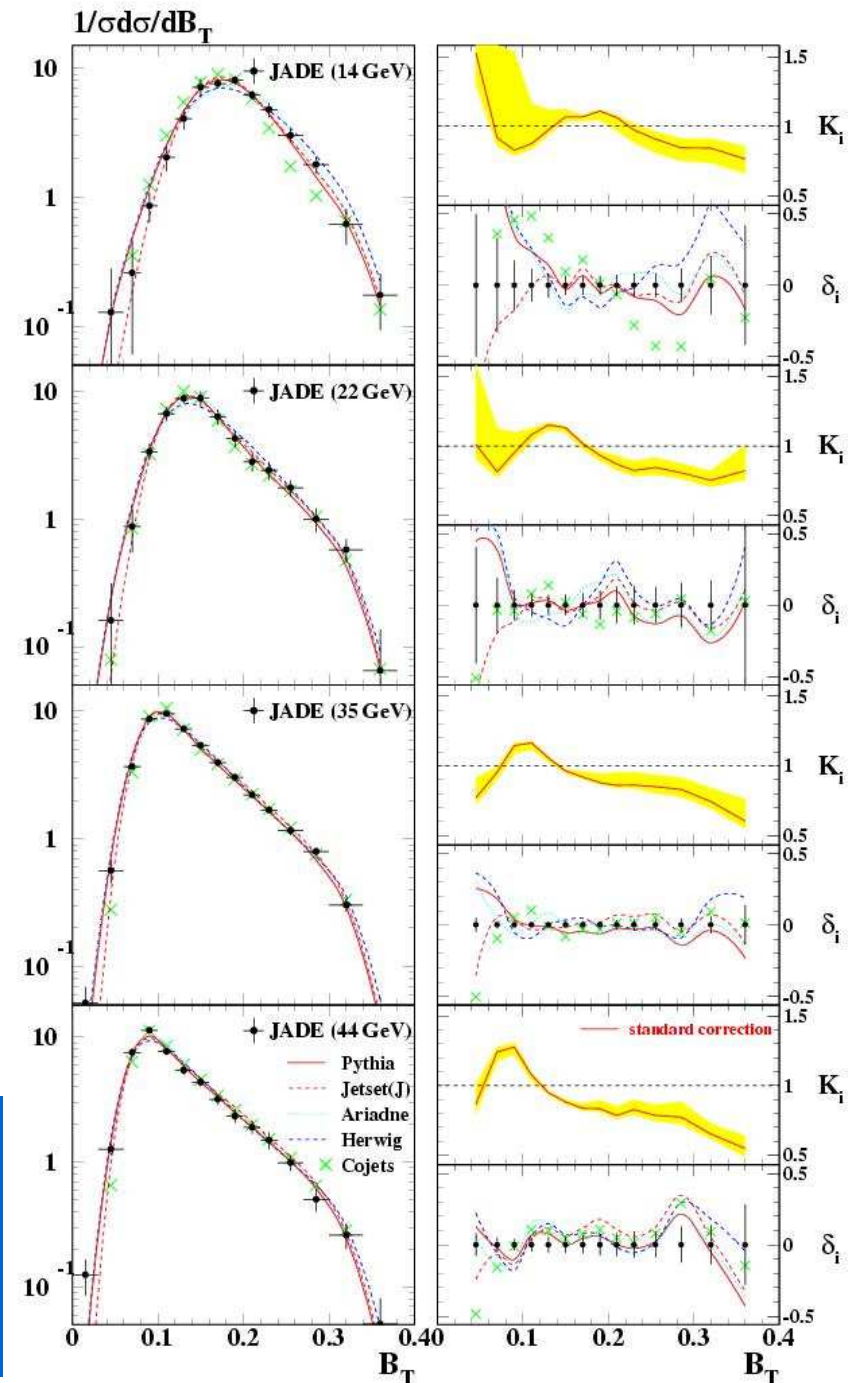
- good at 14+22 GeV, slightly worse at higher \sqrt{s}

COJETS

- disfavoured at 14+22 GeV, remains worse at higher \sqrt{s}

Event shape become more and more “2-jet like” at higher energies:

- ➔ running of α_s
- ➔ hadronization effects



Determinations of α_s



QCD Predictions

$y=1-T$, M_H , B_T , B_W , C , y_{23} ... infrared and collinear safe

Cumulative predictions $R(y)=\int^y dy' 1/\sigma \cdot d\sigma/dy'$:

I. **NLO**: describes “hard” gluon contribution

$$R(y) = 1 + A(y) \cdot \alpha_s + B(y) \cdot \alpha_s^2$$

Problem: divergent for $y \rightarrow 0$ (2 jet region)

II. **NLLA**: describes “softer” gluon contribution

$$R(y) = (1 + C_1 \cdot \alpha_s + C_2 \cdot \alpha_s^2) \exp\{ L g_1(\alpha_s L) + g_2(\alpha_s L) \}$$

...collects large logarithmic contributions $\alpha_s L$ $L = \log(1/y)$

\Rightarrow much better convergence for $y \rightarrow 0$

Problem: not designed for 3 jet region

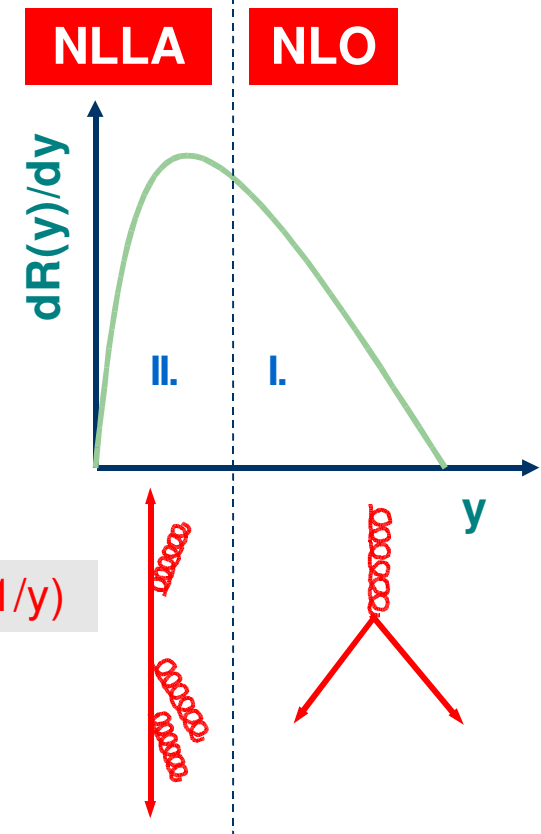
III. **Matching**: NLO + NLLA, e.g.: $\ln(R)$ -matching

$$\begin{aligned} \ln(R(y)) = & L g_1(\alpha_s L) + g_2(\alpha_s L) \\ & - (G_{11} L + G_{12} L^2) \cdot \alpha_s - (G_{22} L + G_{23} L^2) \cdot \alpha_s^2 \\ & + A(y) \cdot \alpha_s + [B(y) - \frac{1}{2} A(y)^2] \cdot \alpha_s^2 \end{aligned}$$

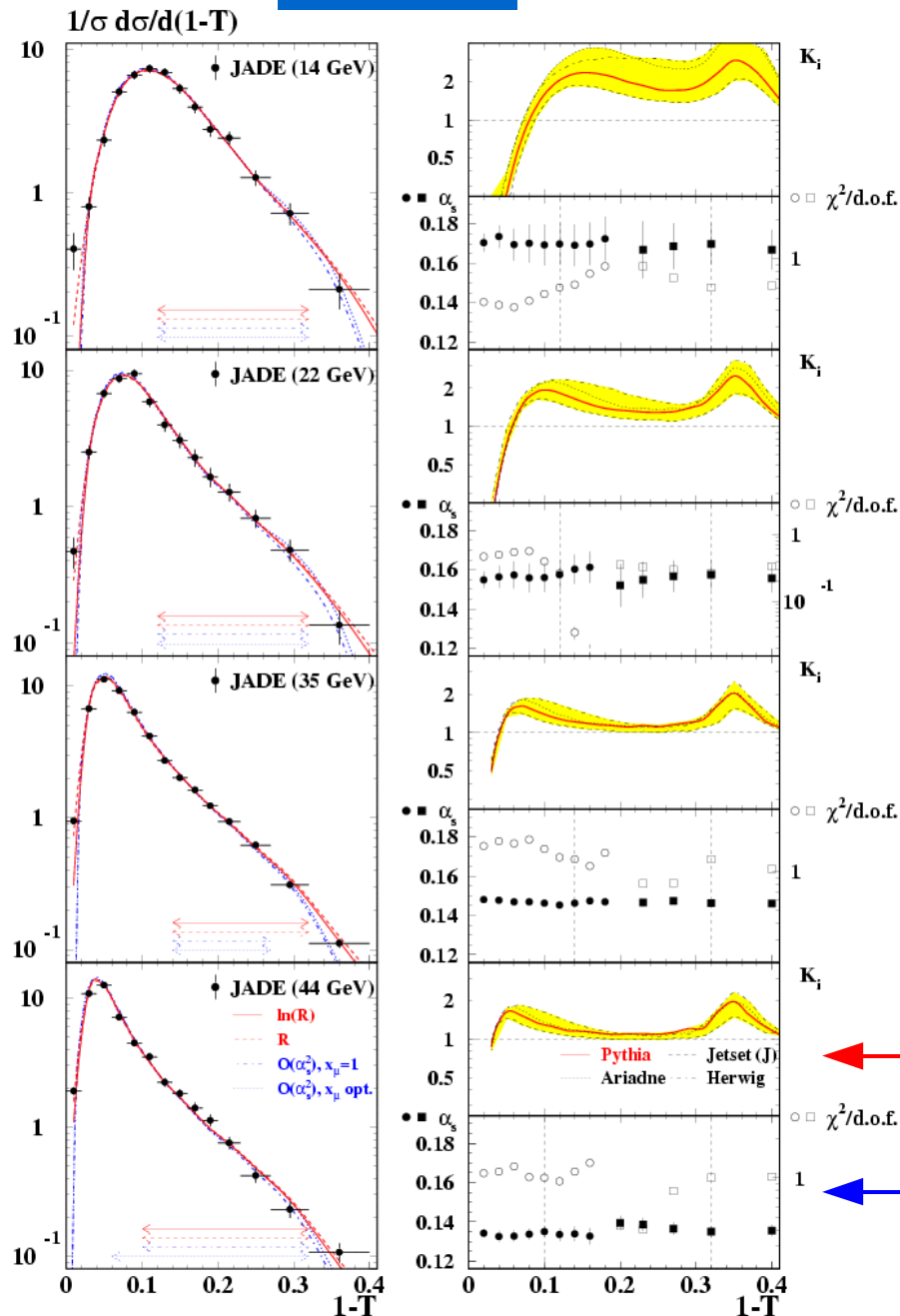
subtract incomplete 2nd order contribution

replace by complete NLO

...avoids double counting



Thrust



α_s -Fits

- α_s is only free parameter
renormalization scale factor fixed:
 $x_\mu = \mu/\sqrt{s} = 1$
- Perform hadronization correction of cumulative predictions $R(y)$



Fit curves:

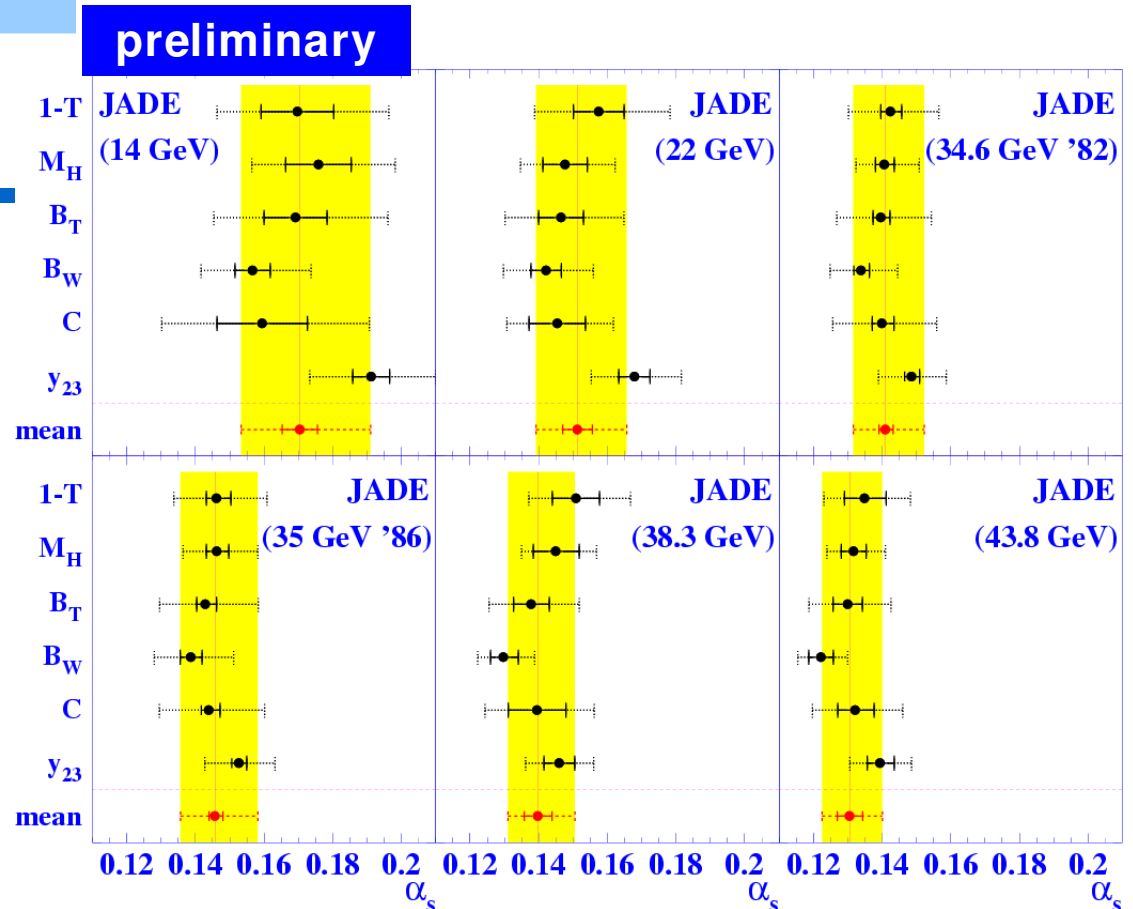
- Typically: $\chi^2/d.o.f. = 0.5 \dots 2.0$
- Stable fits
- Hadronization correction increases drastically for $\sqrt{s} \rightarrow 14 \text{ GeV}$

hadronization correction

α_s and χ^2 dependence of fit range

α_s Results

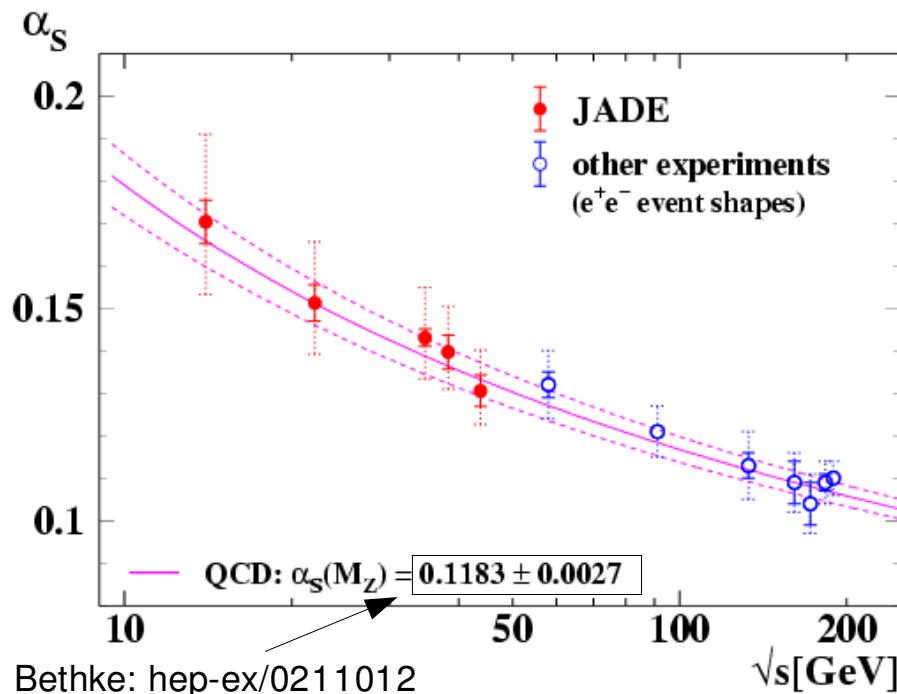
- Results agree within 1-2 σ of exp.+stat. errors
...much better consistency than old PETRA values
- Dominant errors:
 - Renormalization scale ($x_\mu=0.5...2.0$)
...uncertainty significantly reduced w.r.t. NLO
 - 14+22 GeV: hadronization, mass effects



$\langle\sqrt{s}\rangle$ [GeV]	$\alpha_s(\sqrt{s})$	fit error	exp.	hadr.	higher ord.	total
14.0	0.1704	$\pm 0.0051^*$		$+0.0141$ -0.0136	$+0.0143$ -0.0091	$+0.0206$ -0.0171
22.0	0.1513	$\pm 0.0043^*$		± 0.0101	$+0.0101$ -0.0065	$+0.0144$ -0.0121
34.6 ('82)	0.1409	± 0.0012	± 0.0017	± 0.0071	$+0.0086$ -0.0057	$+0.0114$ -0.0093
35.0 ('86)	0.1457	± 0.0011	± 0.0020	± 0.0076	$+0.0096$ -0.0064	$+0.0125$ -0.0101
38.3	0.1397	± 0.0031	± 0.0026	± 0.0054	$+0.0084$ -0.0056	$+0.0108$ -0.0087
43.8	0.1306	± 0.0019	± 0.0032	± 0.0056	$+0.0068$ -0.0044	$+0.0096$ -0.0080

$$\alpha_s(M_Z) = 0.1194 \pm 0.0020(\text{exp+stat}) \pm 0.0051(\text{had}) \begin{matrix} +0.0061 \\ -0.0041 \end{matrix} (\text{theo})$$

Test of the Asymptotic Freedom



$$\alpha_s(\sqrt{s}) = \frac{1}{\beta_0 l} - \frac{\beta_1 \ln l}{\beta_0^2 l^2} + \frac{1}{\beta_0^3 l^3} \left[\frac{\beta_1^2}{\beta_0^2} (\ln^2 l - \ln l - 1) + \frac{\beta_2}{\beta_0} \right]$$

$$l = \ln(\sqrt{s}/\Lambda_{\overline{\text{MS}}})^2$$

$$\beta_0 = \frac{1}{12\pi} (33 - 2N_f)$$

$$\beta_1 = \frac{1}{24\pi^2} (153 - 19N_f)$$

$$\beta_2 = \frac{1}{3456\pi^3} (77139 - 15099N_f + 325N_f^2)$$

- α_s has been “homogeneously” determined from LEP 2 energies down to lowest PETRA energies
- This is the first measurement at 14 and 22 GeV
- PETRA points increase significance of QCD test substantially

QCD fit, exp.+stat. uncertainties
(inner error bars):

$$\Lambda_{\overline{\text{MS}}}^{(5)} = 246 \pm 7 \text{ MeV}$$

$$\alpha_s(M_Z) = 0.1210 \pm 0.0006$$

$$P(\chi^2) = 75\%$$

“ $\alpha_s = \text{const.}$ ”, total errors

(outer error bars):

$$P(\chi^2) = 1.1 \cdot 10^{-5}$$

Excellent agreement with

- ✓ QCD expectation for running of α_s
- ✓ world average value (NNLO)

Moments and 4-Jet Rates (JADE & OPAL)



JADE/OPAL Analysis Framework

- JADE Revival Group has established a “homogeneous” technical framework to analyse multihadronic final states measured by JADE and OPAL:
 - ▶ Data/MC reside in almost identical PAW ntuples
 - ▶ Master analysis program reads JADE and OPAL ntuples and generates all histograms needed (performs event selection, correction of detector effects, etc.)
- Goal for future analyses:
 - ▶ Consistent study of systematics
 - ▶ Consider correlations between the two experiments as much as possible
 - ▶ Apply LEP-QCD Working Group method to combine results of different experiments

Moments of Event Shapes

- α_s analyses of differential distributions compares theory with data only in restricted kinematical regions.
- Complementary approach: Moment analysis
...probes all available phase space

n^{th} moment of event shape distribution:

$$\langle y^n \rangle = \int_0^{y_{\max}} y^n \frac{1}{\sigma} \frac{d\sigma}{dy} dy$$

- QCD expectation obtained by full numerical integration of NLO ME over phase space: $\langle y^n \rangle = A_n \alpha_s + B_n \alpha_s^2$

JADE and **OPAL** have analyzed 1st ... 5th moments



14-44 GeV

ICHEP '04 #5-0502
hep-ex/0408123



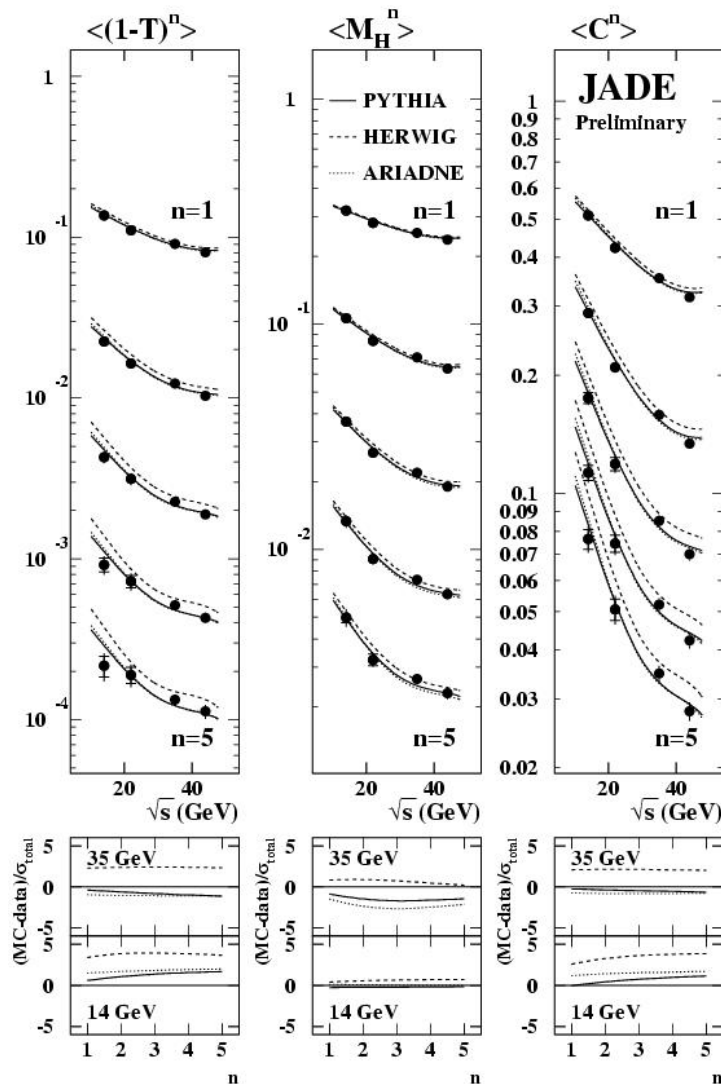
91-209 GeV

ICHEP '04 #5-0527
CERN-EP 04-044

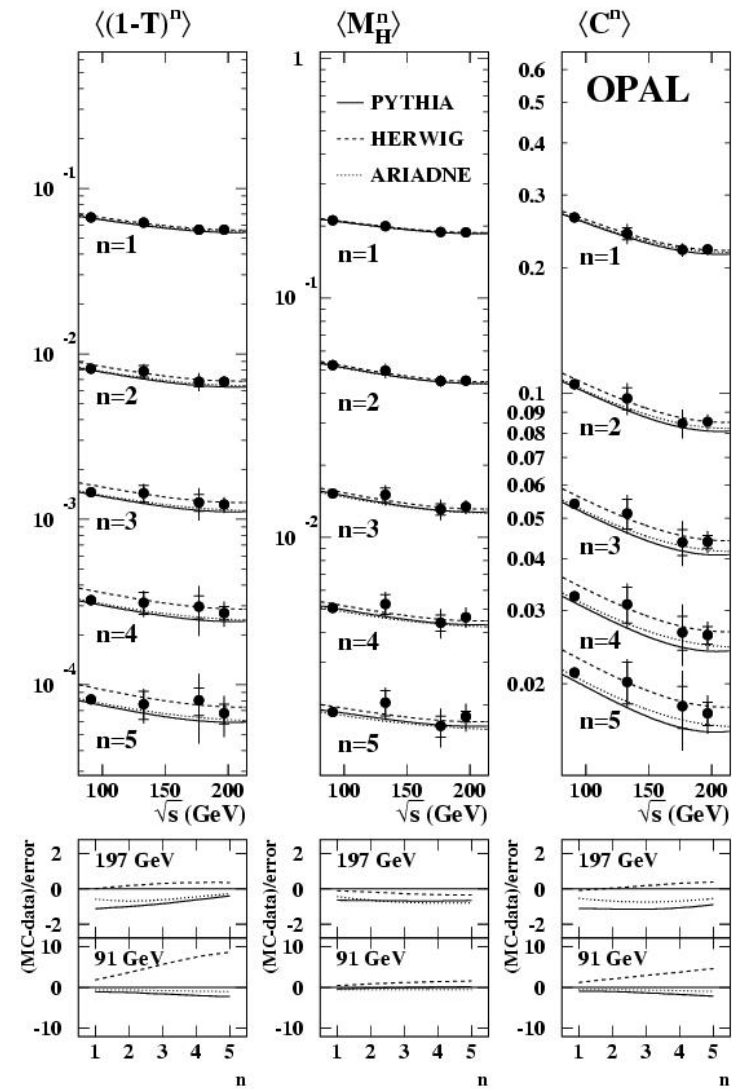
Data vs MC Models

preliminary

JADE



OPAL



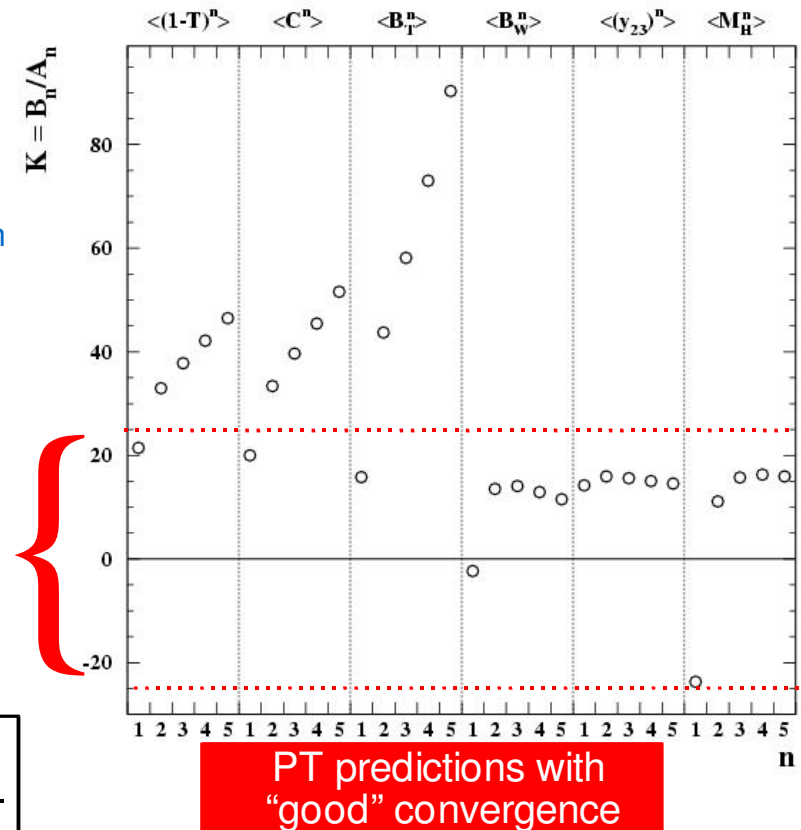
Generally good agreement with MC predictions (PYTHIA, Ariadne)

α_s from Moments

- QCD expectation fitted individually to \sqrt{s} evolution of the moments
 - α_s increases with order n
 - n dependence of α_s is correlated with size of NLO correction $K=B_n/A_n$
- α_s combination (JADE and OPAL separately as yet):
 - consider only converging fits of those predictions with NLO term
 $|K \alpha_s/2\pi| < 0.5 \rightarrow 17$ observables
 - calculate weighted mean:

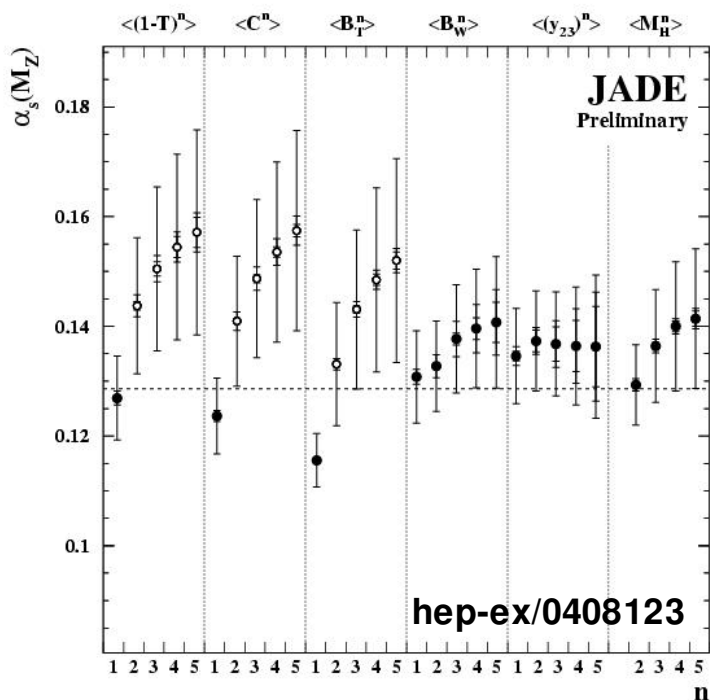
$$\alpha_s(M_Z) = \sum w_i \alpha_{s,i} \quad w_i = \frac{\sum_j (V'^{-1})_{ij}}{\sum_{j,k} (V'^{-1})_{jk}}$$

$$V'_{ij} = V'^{(stat)}_{ij} + V'^{(exp)}_{ij} + V'^{(had)}_{ij} + V'^{(theo)}_{ij}$$



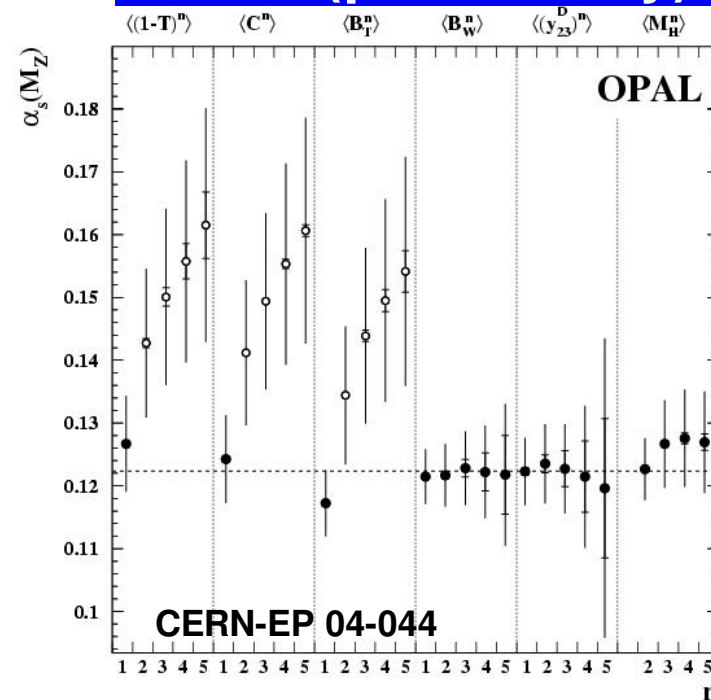
α_s from Moments

JADE (preliminary)



$$\alpha_s(M_Z) = 0.1286 \pm 0.0007^{\text{stat}} \pm 0.0011^{\text{exp}} \pm 0.0022^{\text{had}} \pm 0.0068^{\text{theo}}$$

OPAL (preliminary)



$$\alpha_s(M_Z) = 0.1223 \pm 0.0005^{\text{stat}} \pm 0.0014^{\text{exp}} \pm 0.0016^{\text{had}} \begin{matrix} +0.0054 \\ -0.0036 \end{matrix}^{\text{theo}}$$

- consistent with world average
- α_s from fits of NLO (with $\mu=\sqrt{s}$) to distributions tend to be large as well
- remarkable: theoretical uncertainties are almost competitive with NLO +NLLA analyses of distributions

α_s from 4-Jet Rate

- Measure number of event with 4 jets as a function of a jet resolution parameter y_{cut} using the Durham scheme

NLO prediction $O(\alpha_s^3)$...

$$R_4(y_{\text{cut}}) = \frac{\sigma_{4\text{-jet}}(y_{\text{cut}})}{\sigma_{\text{tot}}} = \left(\frac{\alpha_s C_F}{2\pi} \right)^2 B_4(y_{\text{cut}}) + \left(\frac{\alpha_s C_F}{2\pi} \right)^3 \left[C_4(y_{\text{cut}}) + \frac{3}{2} (\beta_0 \log x_\mu - 1) B_4(y_{\text{cut}}) \right]$$

...matched with NLLA

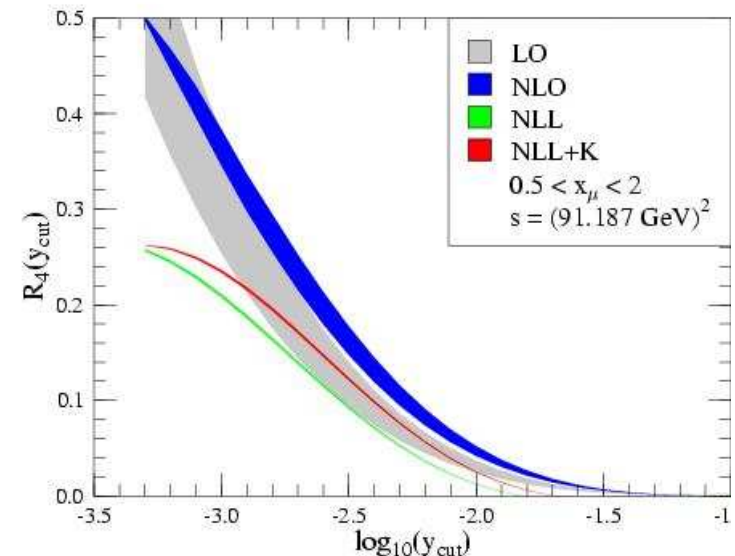
$$R^{\text{match}} = R^{\text{NLLA}} + \left[\left(\frac{\alpha_s C_F}{2\pi} \right)^2 (B_4 - B^{\text{NLLA}}) + \left(\frac{\alpha_s C_F}{2\pi} \right)^3 (C_4 - C^{\text{NLLA}} - \frac{3}{2} (B_4 - B^{\text{NLLA}})) \right]$$

LO/NLO coefficients from integration of ME for $e^+e^- \rightarrow q\bar{q}g\bar{g}, q\bar{q}q'\bar{q}'$

LO/NLO coefficients of NLLA prediction

- Scale uncertainty
 $\Delta R_4(x_\mu) \propto \alpha_s^3 \log x_\mu$

Durham algorithm



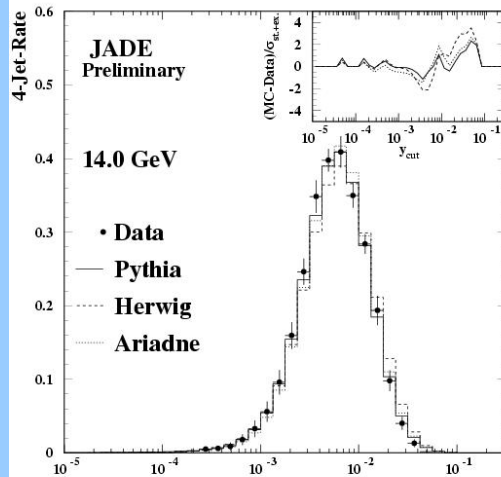
Data vs MC Model

JADE
14-44 GeV

ICHEP '04 #5-0498
hep-ex/0408122

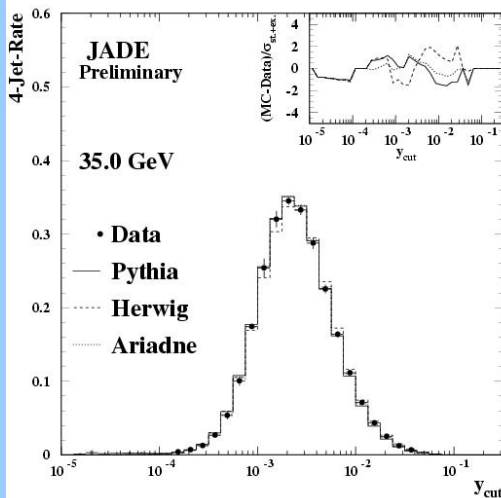
ICHEP '04 #6-0600

OPAL
91-209 GeV

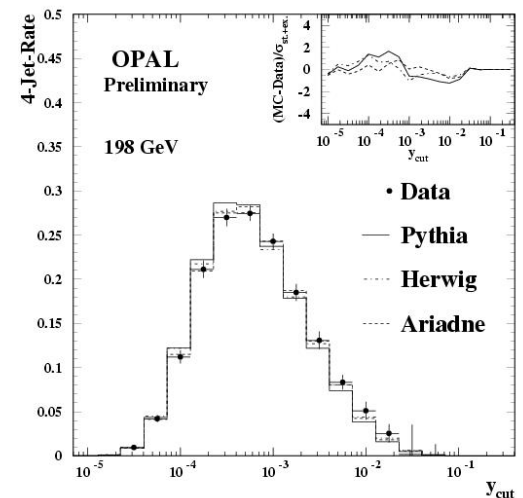
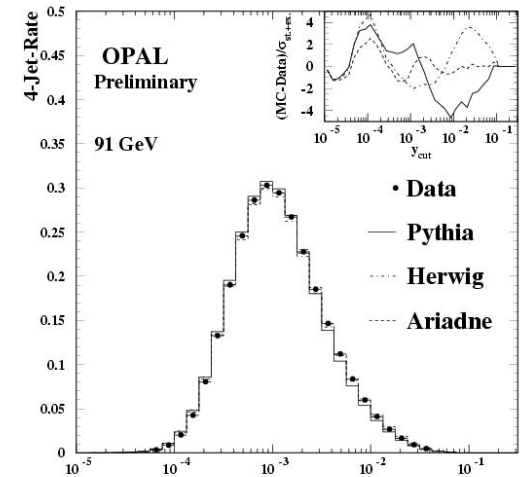


- Single event can contribute to several bins
- Complete covariance matrix needed for α_s fits

Hadron level data
vs.
MC predictions

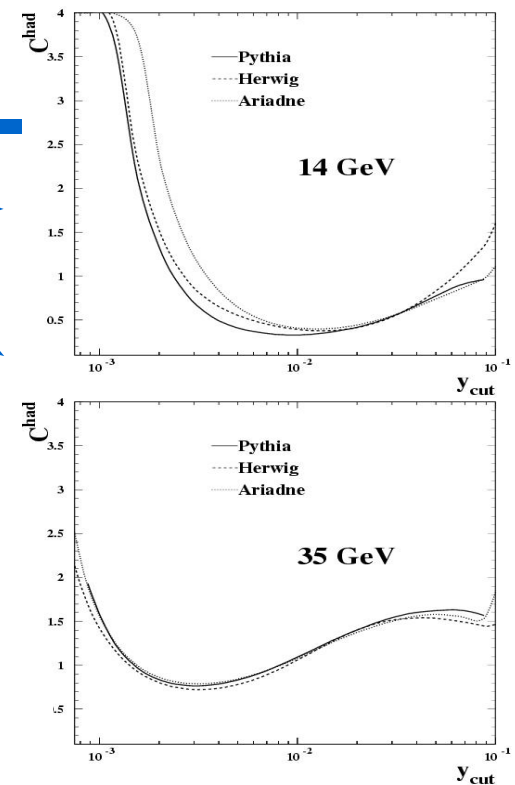


- Good agreement between data and MC model

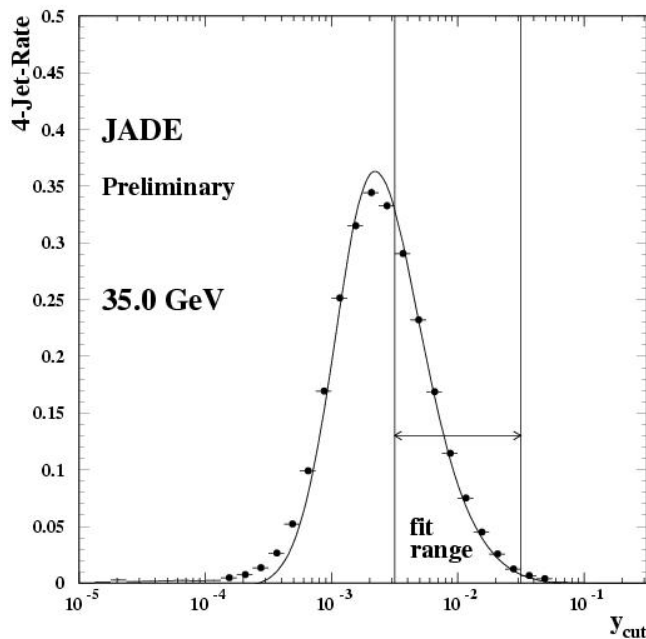


α_s from 4-Jet Rate

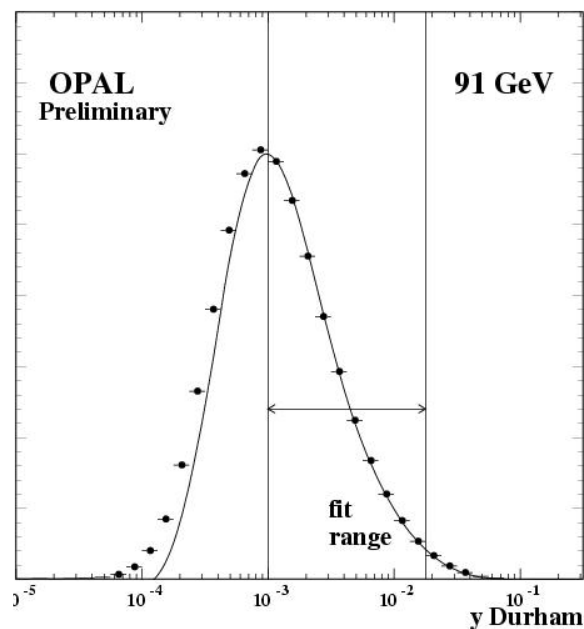
- Hadronization correction to parton level
- Fit with α_s as only free parameter
- Fit ranges:
 - region with moderate hadronization uncertainties
 - stay away from too low y_{cut} values
(region dominated by events with more than 4 jets)



JADE

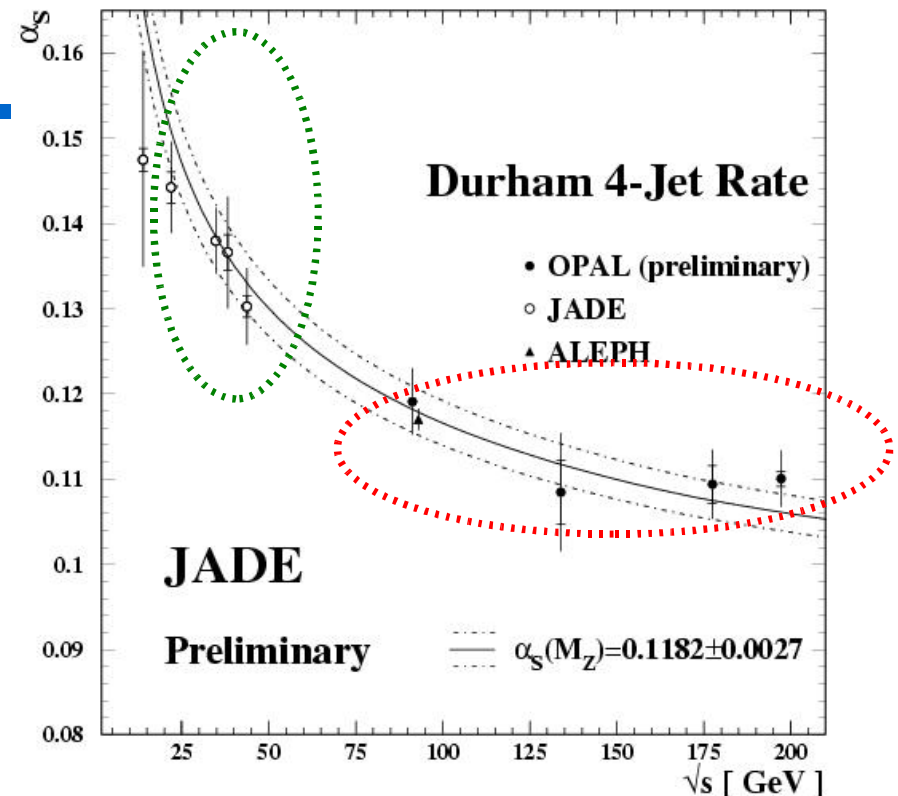


OPAL



α_s from 4-Jet Rate

- Combine results using weighted mean method (JADE and OPAL separately as yet)
- Skip JADE point at 14 GeV because of hadronization uncertainties



JADE (preliminary):

$$\alpha_s(M_Z) = 0.1169 \pm 0.0004^{\text{stat}} \pm 0.0012^{\text{exp}} \pm 0.0021^{\text{had}} \pm 0.0007^{\text{theo}}$$

OPAL (preliminary):

$$\alpha_s(M_Z) = 0.1208 \pm 0.0006^{\text{stat}} \pm 0.0021^{\text{exp}} \pm 0.0019^{\text{had}} \pm 0.0024^{\text{theo}}$$

- Small renormalization scale uncertainties indicate “small” missing higher order contributions ($\Delta R_4(x_\mu)$ might depend on fit range)
- in excellent agreement with world average

Power Corrections



Power Corrections a la DMW

- Classical method to estimate NP effects: MC models
Problem: numerous parameters (parton shower, fragmentation)
- Promising alternative: **Power Corrections (PC)**

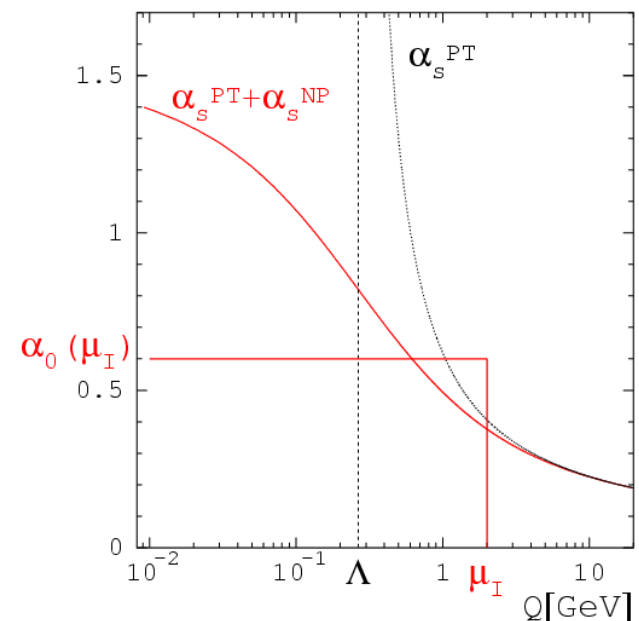
I. Parametrize unknown but analytical behaviour of the strong coupling constant around the Landau pole Λ (0...2GeV)

$$\alpha_0(\mu_I) = \frac{1}{\mu_I} \int_0^{\mu_I} \alpha_s(\mu) d\mu$$

- ▶ integrates over all NP details
- ▶ μ_I separates PT and NP region (usually $\mu_I = 2\text{GeV}$)

II. Dokshitzer, Marchesini, Webber (DMW):

NP structure due to soft gluon radiation at $\mu \approx \Lambda$



DMW Predictions for Event Shapes

NP: general structure

$$\langle y \rangle = \langle y \rangle^{\text{PT}} + \mathcal{D}_y \mathcal{P} \quad (\text{means})$$

$$\frac{d\sigma}{dy}(y) = \frac{d\sigma^{\text{PT}}}{dy}(y - \mathcal{D}_y \mathcal{P}) \quad (\text{distributions})$$

$$\mathcal{P} = \frac{4C_F}{\pi^2} \mathcal{M}_Q^{\mu_1} \left[\alpha_0(\mu_1) - \alpha_S(\mu_R) - \beta_0 \frac{\alpha_S^2(\mu_R)}{2\pi} \left(\ln \frac{\mu_R}{\mu_1} + \frac{K}{\beta_0} + 1 \right) \right]$$

NP: observable specific part

y	$\mathcal{D}_y = \mathcal{D}_y(\alpha_S, y)$
$1 - T$	2
M_H^2	1
C	3π
B_T	$\ln(1/y) + D_T(y, \alpha_S(yQ))$
B_W	$\frac{1}{2} \ln(1/y) + D_1(y, \alpha_S(yQ))$

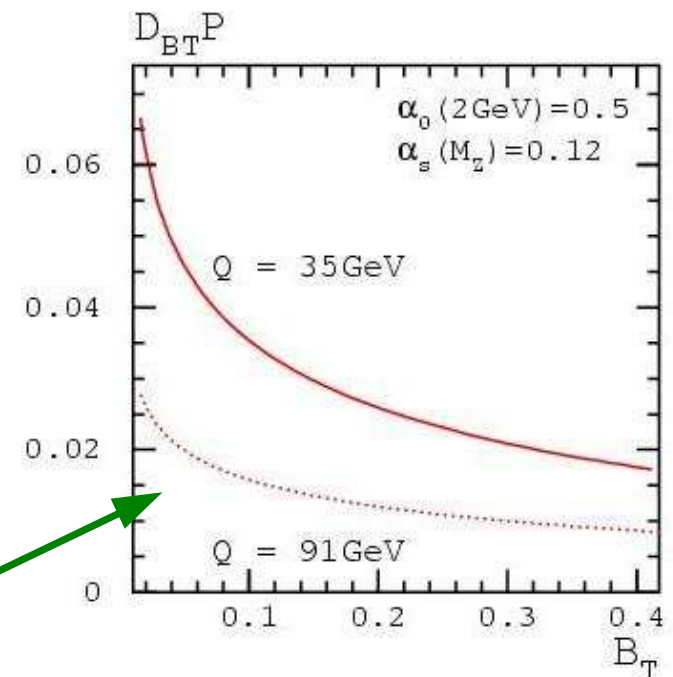
shift

shift+squeeze

y_{23} : no $1/Q$ contribution expected

PT:

NLO+ NLLA, different matching schemes



- α_0 is the only NP parameter
- α_0 is “universal”

Tests of the DMW Model

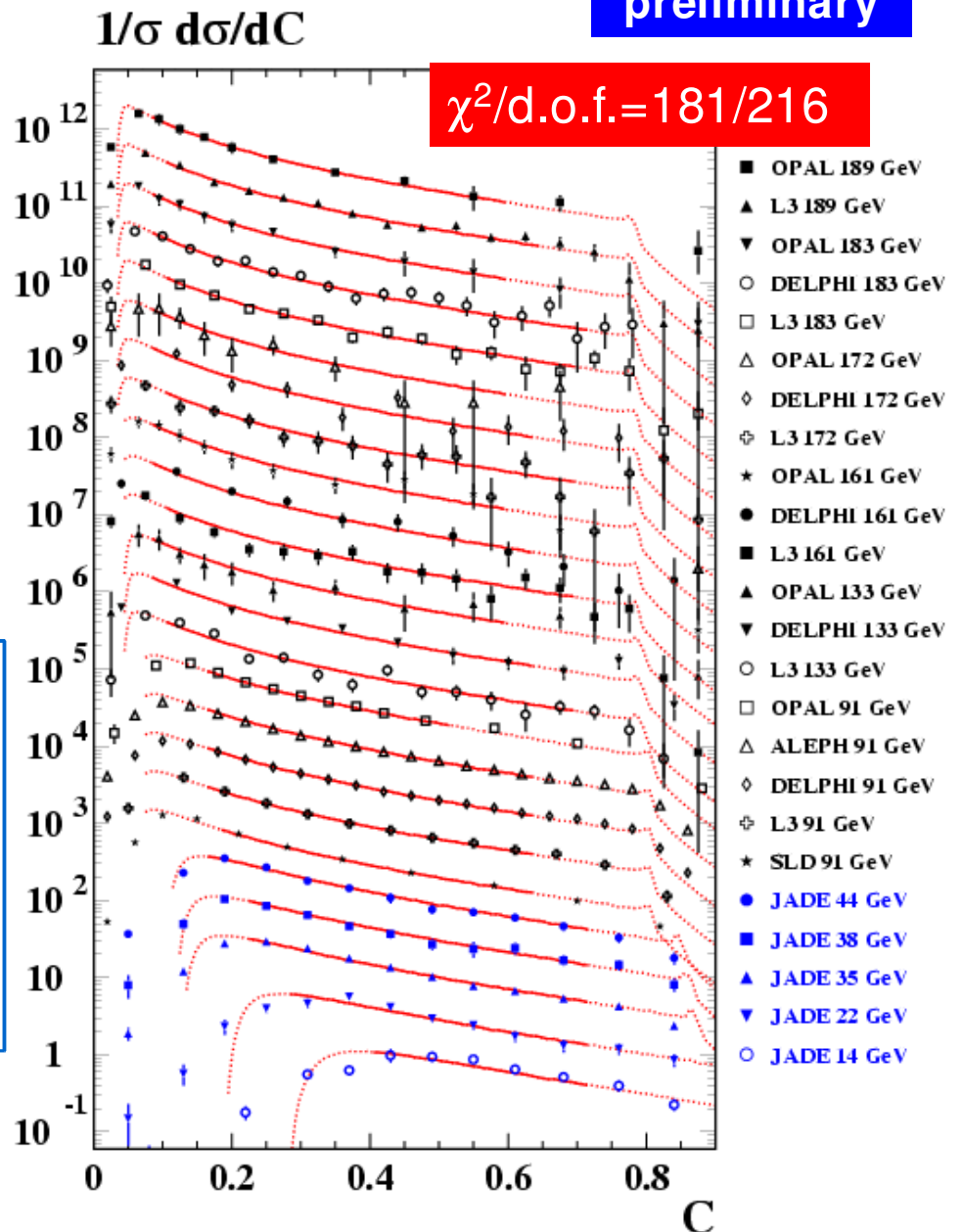
preliminary

- Global fit of PT+PC to overall event shape data from JADE and measurements published by other experiments at PETRA, LEP, SLC, PEP, TRISTAN
- 2 free parameters:
 $\alpha_s(M_Z)$, $\alpha_0(\mu_1)$

Data sets

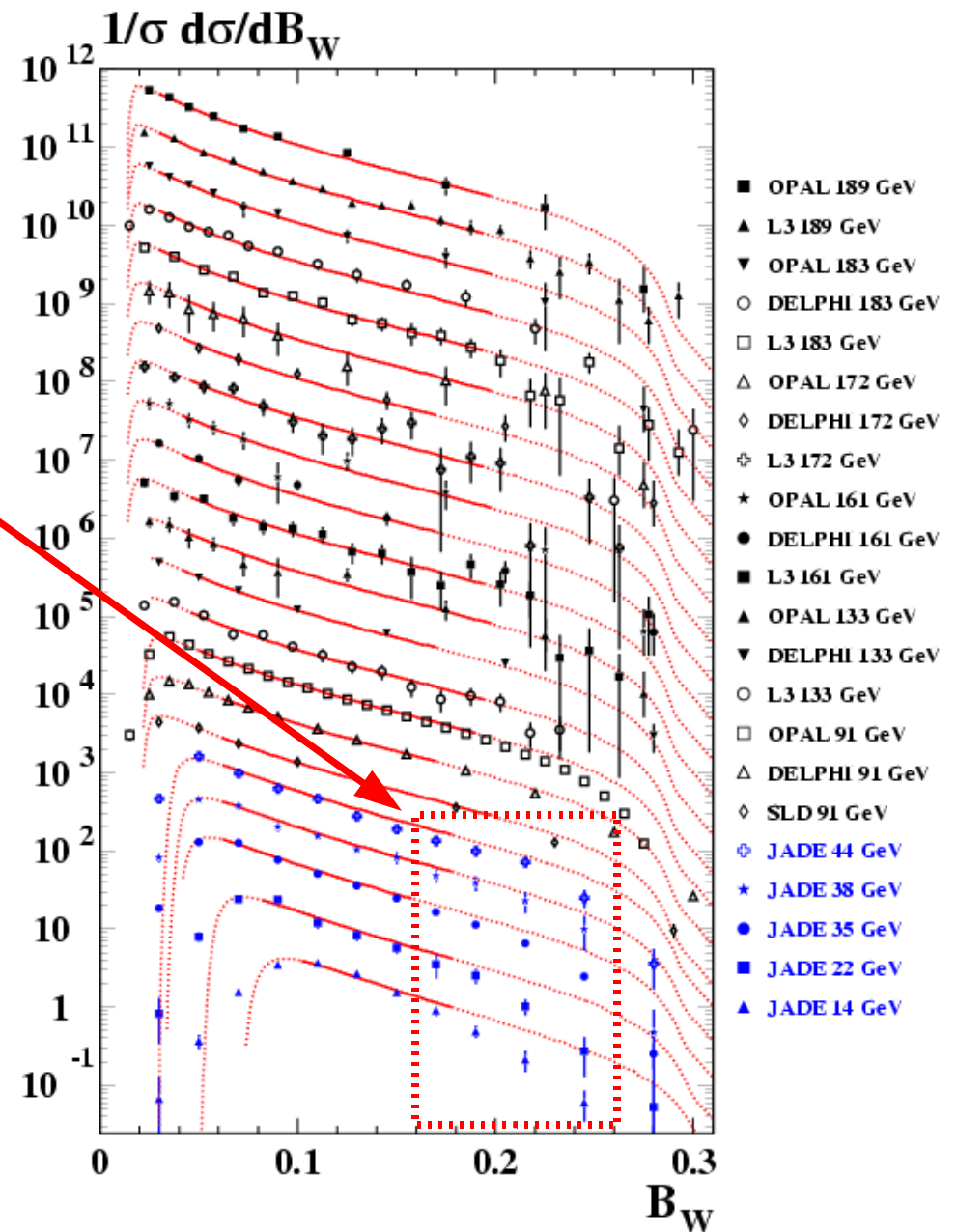
Accelerator	\sqrt{s} [GeV]	$1 - T$	M_H	B_T, B_W, C
PETRA (JADE, TASSO)	12-47	102000		43700
PEP (HRS, MARK II)	29	28300		
TRISTAN (AMY)	55-58	1900		
LEP I (ADLO*)	91		$\mathcal{O}(10^6)$	
SLC (SLD)	91		37200	
LEP II (ADLO*)	133-189		15600	

analysis covers the energy range 14-189 GeV



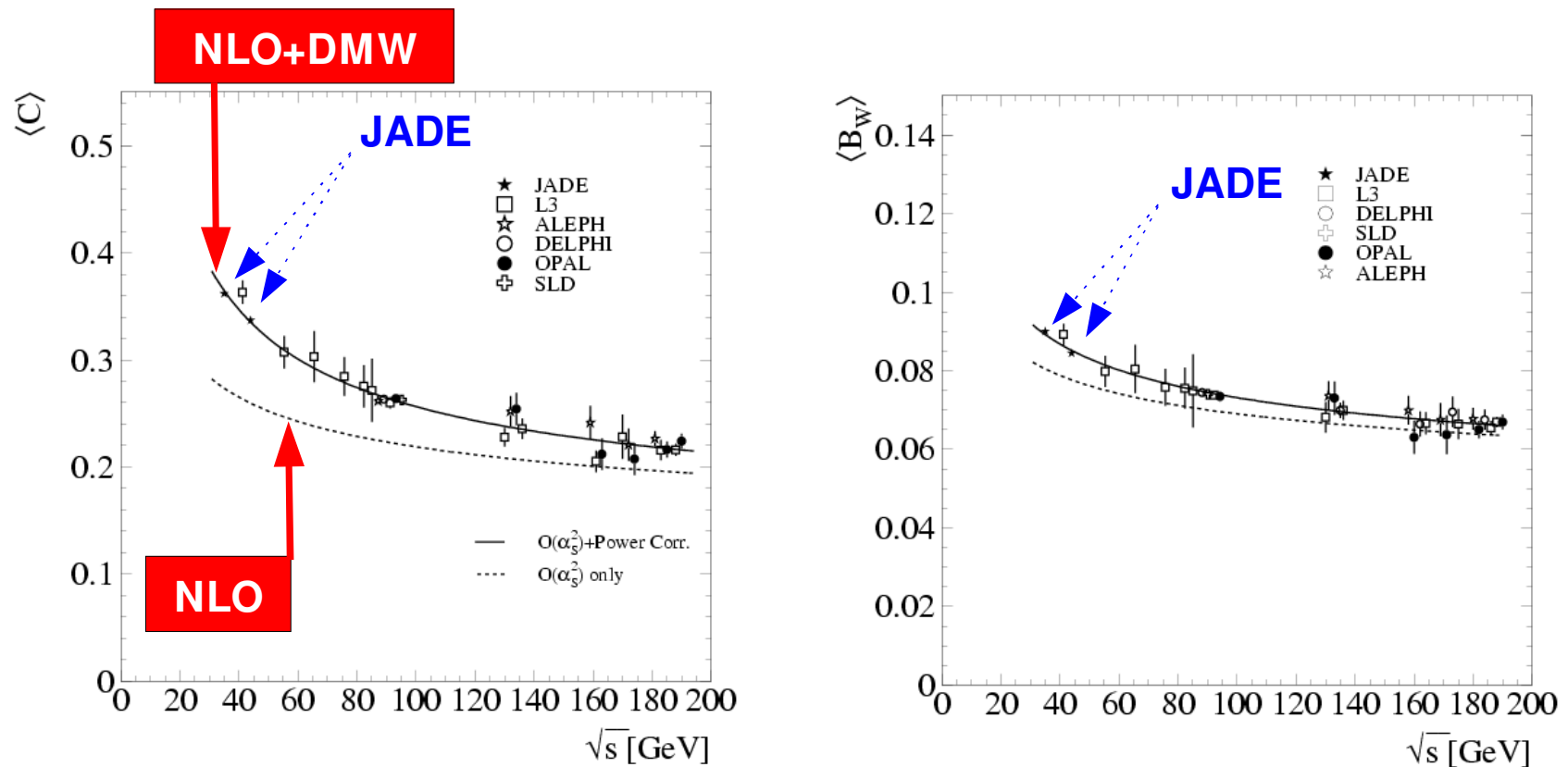
Tests of the DMW Model

- Model works well for T , C , B_T
- DMW predictions for the less inclusive variables M_H , B_W have problems at PETRA energies:
significant excess in 3 jet region
 (but: also problems with PT part of B_W)



Tests of the DMW Model

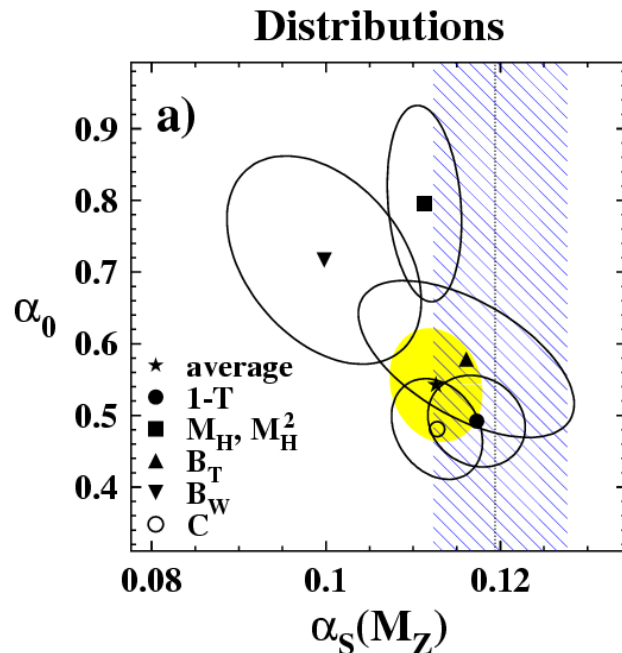
- DMW predictions for **mean values** of event shapes:



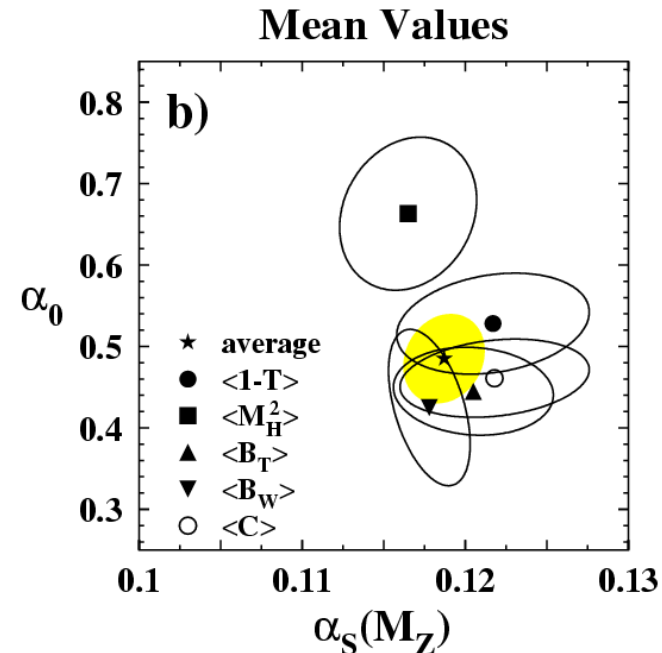
[These plots do not include JADE update at 14+22 GeV]

- Fits mainly constrained by JADE and LEP-I data points
- Model works here well for all variables

α_s and α_0 from DMW Fits



Distributions	fit	exp.	theo.
$\alpha_s(M_{Z^0}) = 0.1126 \pm 0.0005 \pm 0.0037$			$+0.0044$ -0.0030
$\alpha_0(2 \text{ GeV}) = 0.542 \pm 0.005 \pm 0.032$			$+0.084$ -0.060

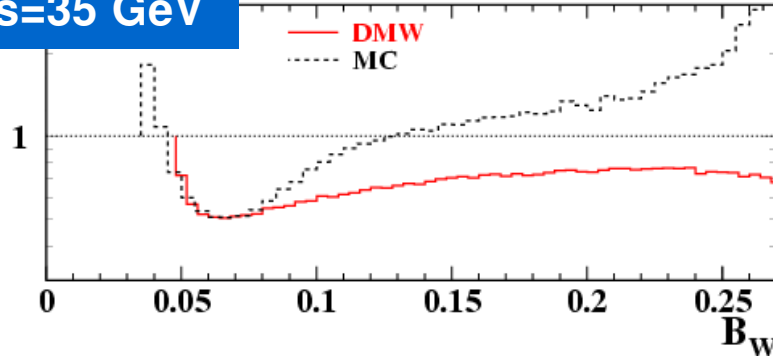


Mean Values	fit	exp.	theo.
$\alpha_s(M_{Z^0}) = 0.1187 \pm 0.0014 \pm 0.0001$			$+0.0028$ -0.0015
$\alpha_0(2 \text{ GeV}) = 0.485 \pm 0.013 \pm 0.001$			$+0.065$ -0.043

- Individual results consistent within 1-2 σ of total errors
- α_0 universal at 20% level
...corresponds to uncertainty of $O(\alpha_s^2)$ evaluation of power corrections ("Milan factor")

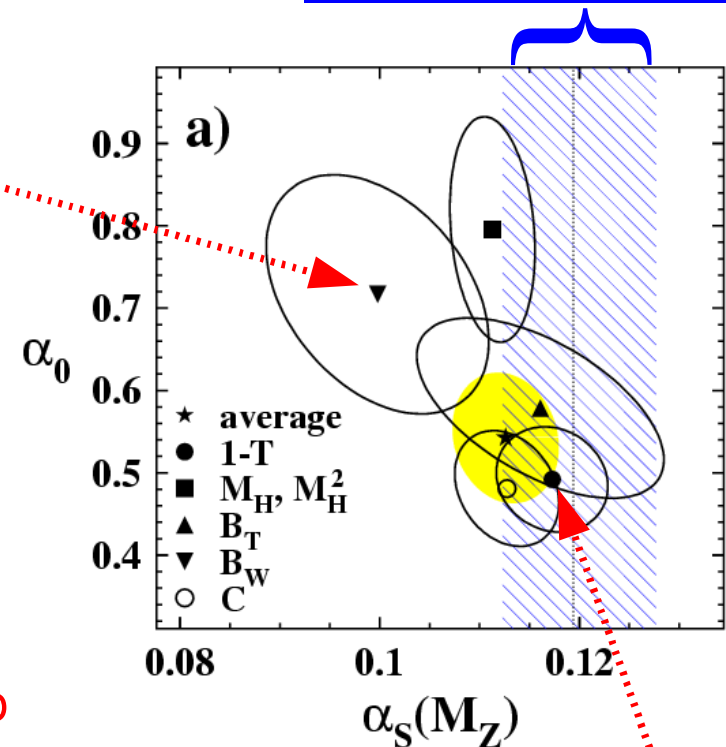
DMW vs. MC

$\sqrt{s}=35$ GeV

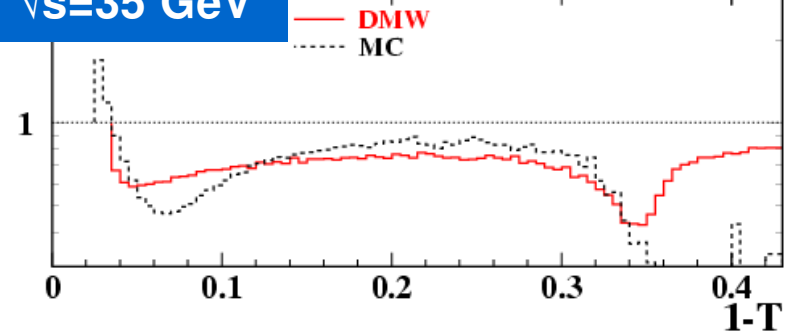


- PT spectrum of B_W , M_H much less squeezed by DMW model than by classical hadronization models
Interplay between α_s and α_0 allows fit to compensate for “missing squeeze” by choosing small α_s values
- systematically lower α_s results from power corrections for differential distributions

classical method

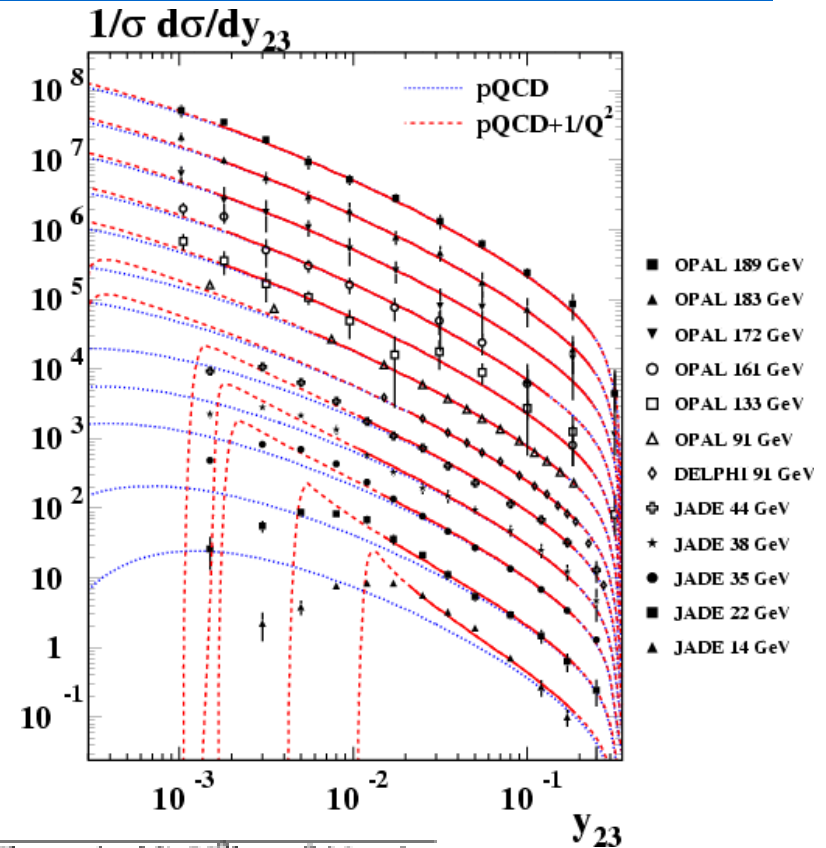


$\sqrt{s}=35$ GeV



Power Corrections to y_{23} ?

- DMW: $1/Q$ coefficient = 0
- Corrections of type $1/Q^2$, $\ln Q/Q^2$ expected, but no detailed prediction exist.
- JADE data at 14+22 GeV would probably help to detect higher order terms more easily.
- Example: assume same NP structure but $A_{10}/Q + A_{20}/Q^2$ dependence:



		$\alpha_s(M_{Z^0})$	$A_{10}[\text{GeV}]$	$A_{20}[\text{GeV}^2]$	$\chi^2/\text{d.o.f.}$
I	pQCD	0.1147 ± 0.0005	—	—	59.7/100
	pQCD	0.1152 ± 0.0005	—	—	151/107
II	pQCD + A_{10}/Q	0.1124 ± 0.0006	0.062 ± 0.008	—	98.2/106
	pQCD + A_{20}/Q^2	0.1133 ± 0.0005	—	2.25 ± 0.18	71.2/106
	pQCD + $A_{10}/Q + A_{20}/Q^2$	0.1128 ± 0.0007	0.018 ± 0.014	1.94 ± 0.31	69.7/105

compatible with 0

$1/Q$

$1/Q^2$

6σ effect

Color Factors from Event Shapes

QCD color factors

	$\sim \alpha_s C_F$
	$\sim \alpha_s C_A$
	$\sim \alpha_s T_F N_f$

...relative weights of the fundamental vertices are determined by SU(3):

- $C_F = 4/3$
- $C_A = 3$
- $T_F N_f = 1/2 N_f$

Shape variables have known color structure:

➔ Running of α_s

$$\beta_0 = \beta_0(C_A, N_F),$$

$$\beta_1 = \beta_1(C_A, C_F, N_F)$$

➔ PT prediction

$$A \propto C_F,$$

$$B = B(C_A, C_F, N_F)$$

$$NLLA = NLLA(C_A, C_F, N_F)$$

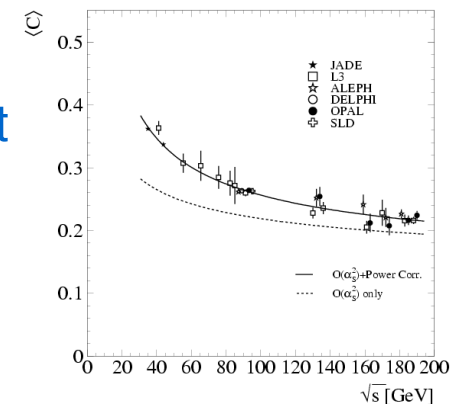
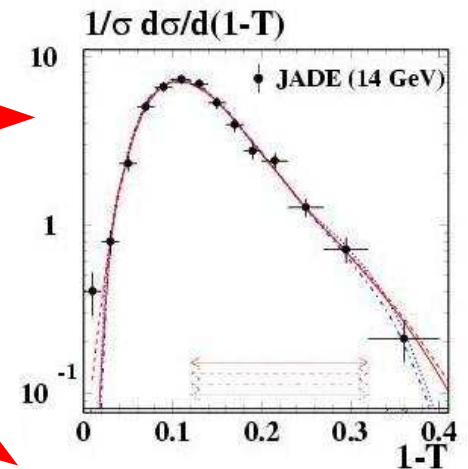
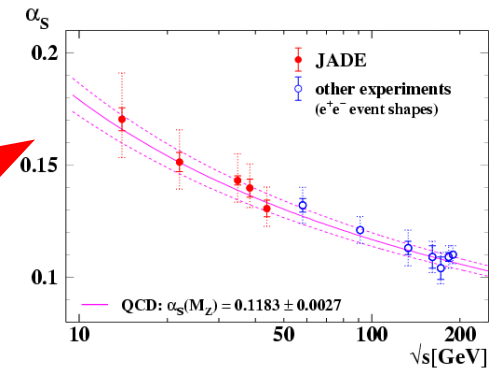
➔ Power Corrections

$$P = P(C_A, C_F, N_F)$$

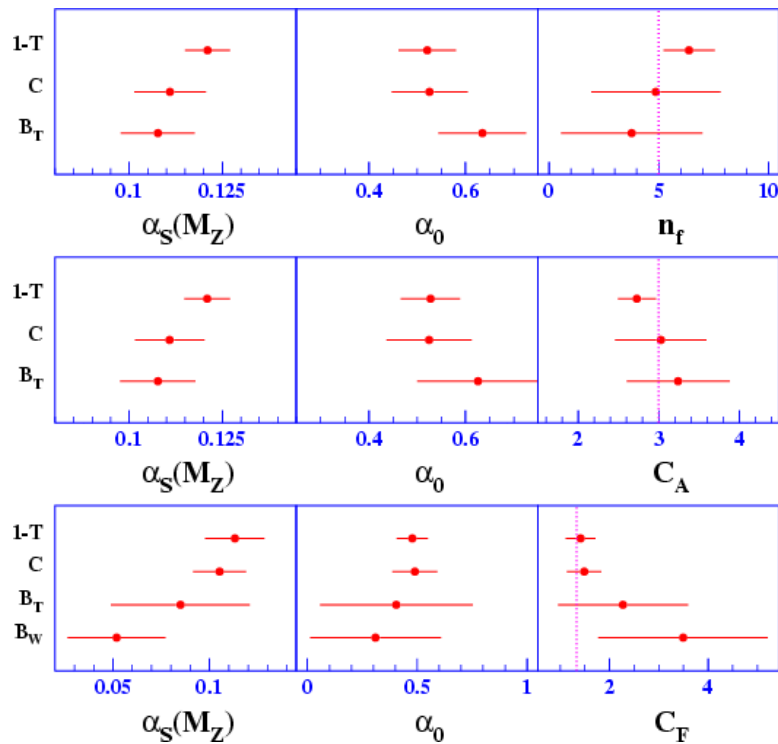
$$M = M(C_A, N_F)$$

$$D_y = D_y(C_A, C_F, N_F)$$

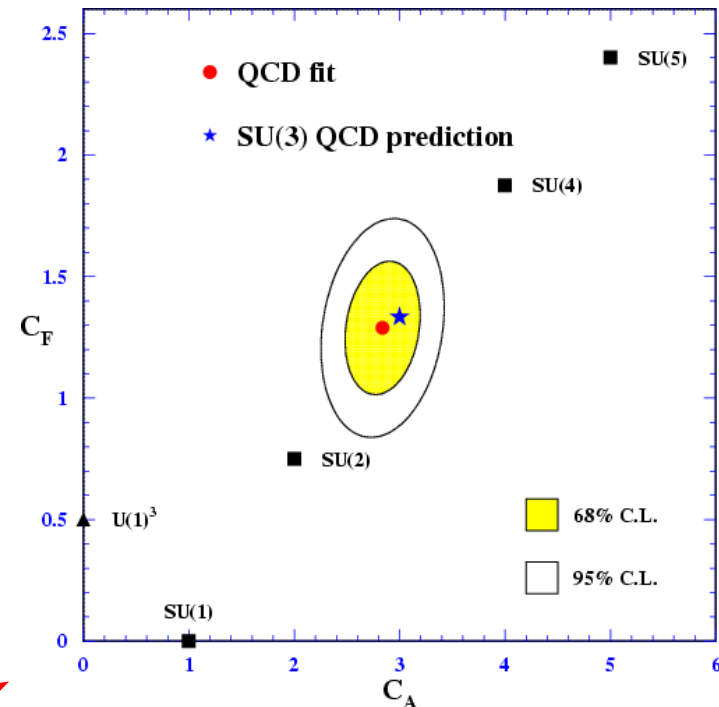
DMW allows measurement w/o bias from color structure of MC models



Color Factors from Event Shapes (2)



	Fit α_S and α_0 and (C_A or C_F or N_f)		Fix α_0 and N_f and fit α_S and C_A and C_F		QCD
	$1 - T$	C	$1 - T$	C	
C_A	2.7 ± 0.2	3.0 ± 0.6	2.7 ± 0.2	3.0 ± 0.5	3
C_F	1.4 ± 0.3	1.5 ± 0.4	1.3 ± 0.2	1.3 ± 0.5	4/3
N_f	6.4 ± 1.2	4.9 ± 3.0	—	—	5



$$C_F = 2.84 \pm 0.24 \quad (\text{QCD:3})$$

$$C_A = 1.29 \pm 0.18 \quad (\text{QCD:4/3})$$

- errors competitive with classical 4-jet angular correlation analyses
- need JADE data to constrain the fit

Summary and Conclusions



Summary I

- NLO+NLLA calculations for event shapes first time applied to PETRA data
- Better calculations gives now a consistent picture of individual α_s at PETRA energies

recent JADE results

- Differential event shapes:

JADE: $\alpha_s(M_Z) = 0.1194^{+0.0082}_{-0.0068}$ (prel.)

LEP+SLC: $\alpha_s(M_Z) = 0.121 \pm 0.006$

LEP2: $\alpha_s(M_Z) = 0.120 \pm 0.007$

- Moments:

JADE: $\alpha_s(M_Z) = 0.1286 \pm 0.0072$ (prel.)

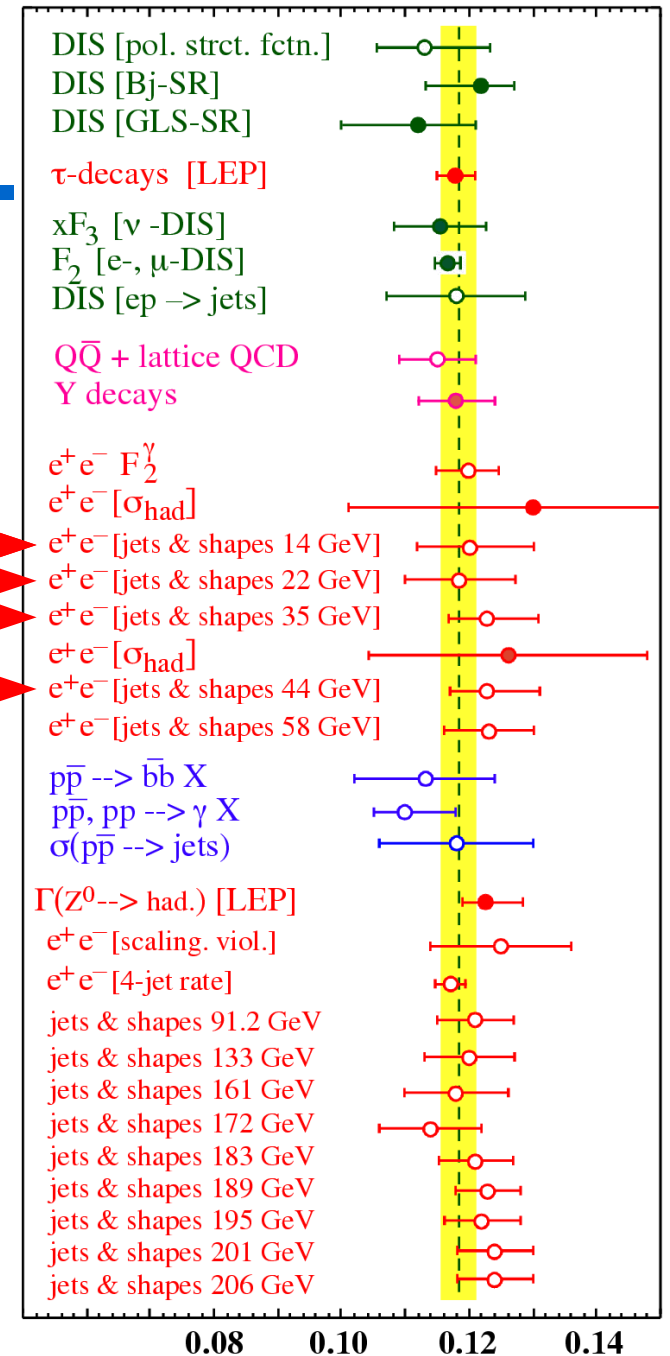
OPAL: $\alpha_s(M_Z) = 0.1223 \pm 0.0059$ (prel.)

- 4-jet rate:

JADE: $\alpha_s(M_Z) = 0.1169 \pm 0.0026$ (prel.)

OPAL: $\alpha_s(M_Z) = 0.1208 \pm 0.0038$ (prel.)

- Overall consistent picture of results from different experiments and methods!**



Bethke 2004, hep-ex/0407021 $\alpha_s(M_Z)$

Summary II

- Power corrections useful to describe event shape data from PETRA to LEP2 energies

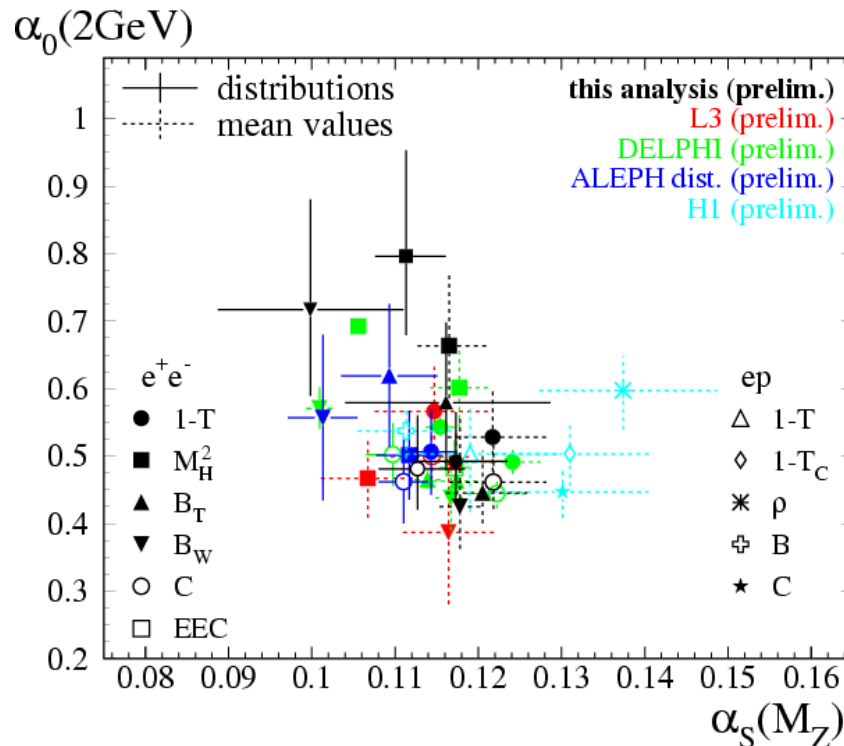
- NP parameter α_0 is universal at a level of 20%**

Distributions:

$$\alpha_s(M_Z)=0.113^{+0.006}_{-0.005} \quad \alpha_0(2\text{GeV})=0.54^{+0.09}_{-0.07}$$

Mean values:

$$\alpha_s(M_Z)=0.119^{+0.003}_{-0.002} \quad \alpha_0(2\text{GeV})=0.49^{+0.07}_{-0.05}$$



- Nice agreement also with other measurements, but clearly improved calculation for more observables needed
- SU(3) structure confirmed in a complementary way**

A Comment on Archiving...

- Archived data of finished experiments might be valuable sources for future analyses:
 - ▶ Was the pentaquark already visible at LEP?
 - ▶ Where was the $D_s^+\pi^0$ resonance before BaBar?
- Long-term maintenance of data+software of an experiment after shutdown is a highly non-trivial task! Things to consider:
 - ▶ Keep software platform independent. At least test on different machines using different compilers.
 - ▶ Provide detailed documentation.
 - ▶ Which data carrier has the longest lifetime?
Are there devices available in future which can read 10 years old data carriers? (Commercial products?)
(...recall JADE data rescue drama 1997, i.e. ~10 years after PETRA shutdown)

Conclusions

- JADE revival and reanalysis project established in HEP community.
- Data and software from the JADE experiment were successfully resurrected.
- Recent state-of-the-art analyses with JADE data proves to be a valuable counterpart to LEP.
- Results provide new stringent test of perturbative and non-perturbative aspects of Quantum Chromodynamics.

**Keep the data and software alive,
it's worth it!!!**

Backup Slides



Tracking/Calorimetry: JADE vs OPAL

	Parameter	JADE	OPAL
Dimensions	overall length	8 m	12 m
	overall height	7 m	12 m
Tracking system	length	2.4 m	4 m
	outer radius	0.8 m	1.85 m
	transv. momentum A	0.04	0.02
	resolution $\sigma(p_t)/p_t$ B	0.018	0.0015
	spatial $r - \phi$	180 $\mu\text{m}/110 \mu\text{m}$	135 μm
	resolution z	1.6 cm	4.5—6 cm (100—350 μm)
	double hit resol.	7.5 mm/2 mm	2.5 mm
	gas composition	88.7%/8.5%/2.8%	88%/9.4%/2.6%
	argon/methane/isobutane		
	gas pressure	4 bar	4 bar
	max. no. of hits	48	159
	reachable in	0.83 $\cdot 4\pi$	0.73 $\cdot 4\pi$
	at least 8 hits	0.97 $\cdot 4\pi$	0.98 $\cdot 4\pi$
	reachable in		
	magnetic field	0.48 T	0.435 T
Electromagnetic calorimetry	energy A	0.015	0.002
	resolution $\sigma(E)/E$ B	0.04	0.063
	solid angle coverage	90%	98%
	angular resolution	7 mrad	2 mrad
	radial extent	1—1.4 m	2.5—2.8 m
	length	3.6 m	7 m
	barrel polar angle covered	$> 32^\circ$	$> 36^\circ$
	radiation depth	12.5 $X_0/15.7 X_0$	24.6 X_0
	granularity	8.5 $\times 10 \text{ cm}^2$	10 $\times 10 \text{ cm}^2$
	outer radius	0.9 m	1.8 m
	endcap polar angle covered	$> 11^\circ$	$> 11^\circ$
	radiation depth	9.6 X_0	22 X_0
	granularity	14 $\times 14 \text{ cm}^2$	9 $\times 9 \text{ cm}^2$

MH Selection JADE vs OPAL

- Main cuts:

Reaction to be suppressed	Cut variable	JADE	OPAL
2-lepton events	n_{ch}	≥ 3 long tracks and ≥ 4 central tracks	≥ 7
	n_{cal}	—	≥ 7
	E_{shw}	> 3.0 GeV (barrel) or > 0.4 GeV (per endcap)	—
2-photon events	E_{vis}/\sqrt{s}	> 0.5	> 0.1
	p_{bal}	< 0.4	< 0.6
other	$ \cos \theta_T $	< 0.8	< 0.9
	$ z_{vert} $	< 15 cm	—

PETRA versus LEP

Parameter	PETRA	LEP
running period	1978–1986	1989–2000
circumference [km]	2.3	26.7
c.m.s. energy [GeV]	12–46.7	91–200
injection energy [GeV]	7	20
interaction points	4	4
bunches per beam	2	4/8
bunch crossing frequency [kHz]	250	45/90
particles per bunch [10^{10}]	26	30
luminosity [$10^{30} \text{cm}^{-2} \text{sec}^{-1}$]	24 (at $\sqrt{s} = 35.0 \text{ GeV}$)	24 (at $\sqrt{s} = 91 \text{ GeV}$) 50 (at $\sqrt{s} > 91 \text{ GeV}$)
bunch size horiz. [μm] \times vert. [μm] \times longit. [cm]	$430 \times 13 \times 1.3$ (at $\sqrt{s} = 35.0 \text{ GeV}$)	$200 \times 8 \times 1$

Longitudinal Cross Section σ_L

Differential cross section for inclusive hadron production:

$$\frac{1}{\sigma_{\text{tot}}} \cdot \frac{d^2\sigma^h}{dx d(\cos\theta)} = \frac{3}{8} (1 + \cos^2\theta) \mathcal{F}_T^h(x) + \frac{3}{4} (\sin^2\theta) \mathcal{F}_L^h(x) + \frac{3}{4} (\cos\theta) \mathcal{F}_A^h(x)$$

transverse

longitudinal

asymmetric

fragmentation functions

x = fractional particle momentum

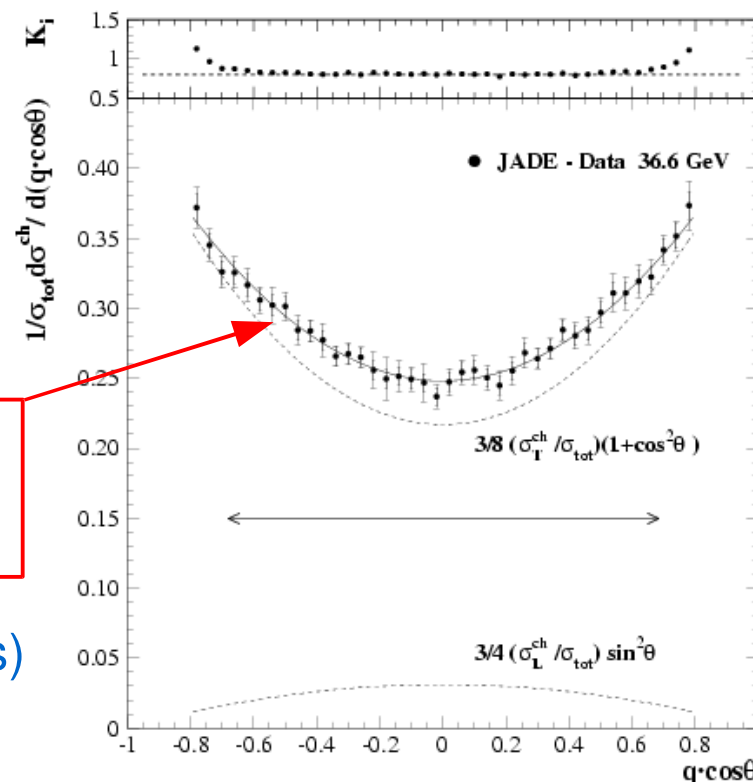
Θ = \angle (incoming particle, outgoing hadron)

- Longitudinal part comes from gluon radiation in quark/anti-quark system
- Asymmetric part not considered because no exp. distinction between quark and anti-quark

$$\frac{\sigma_{T,L}}{\sigma_{\text{tot}}} \equiv \frac{1}{2} \sum_h \int dx x \cdot \mathcal{F}_{T,L}^h(x)$$

$$\frac{1}{\sigma_{\text{tot}}} \cdot \frac{d\sigma^{\text{ch}}}{d(q \cdot \cos\theta)} = \frac{3}{8} \eta^{\text{ch}} \left[\frac{\sigma_L}{\sigma_{\text{tot}}} (1 - 3\cos^2\theta) + (1 + \cos^2\theta) \right]$$

- measure $\cos(\theta)$ distribution (chrgd particles)
- fit ρ_L/ρ_{tot} and η^{ch} (corrects for neutral particles)



Measurement of $\sigma_L/\sigma_{\text{tot}}$

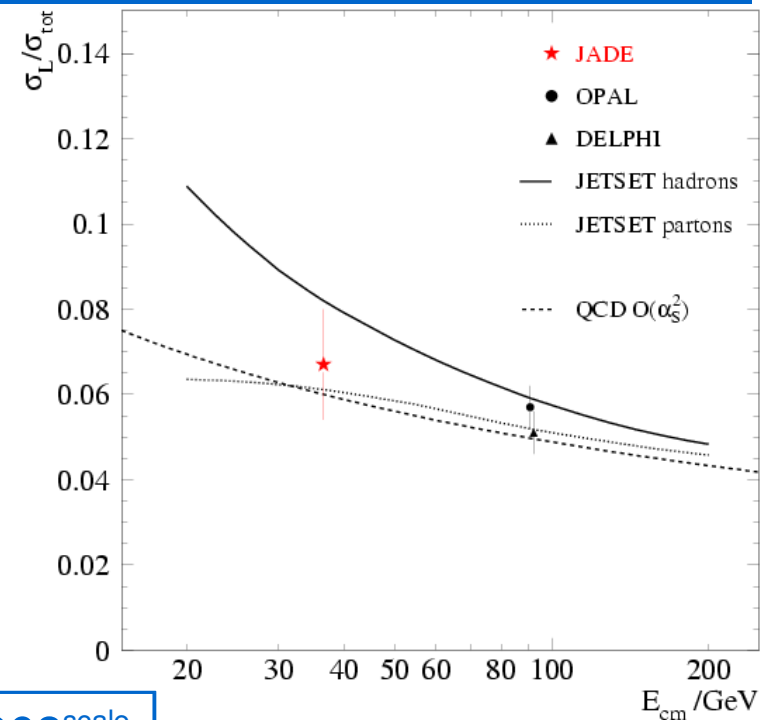
Result:

$$\rho_L/\rho_{\text{tot}} = 0.067 \pm 0.011^{\text{stat}} \pm 0.007^{\text{sys}}$$

- combined 35+44 GeV analysis
- precision is limited by statistics of data and old JADE MC samples
- only measurement below Z peak**

$$\Downarrow \left(\frac{\sigma_L}{\sigma_{\text{tot}}} \right)_{\text{PT}} = \frac{\alpha_S}{\pi} + 8.444 \left(\frac{\alpha_S}{\pi} \right)^2$$

$$\alpha_S(36.6 \text{ GeV}) = 0.150 \pm 0.020^{\text{stat}} \pm 0.013^{\text{sys}} \pm 0.008^{\text{scale}}$$



- Power corrections:

$$\alpha_S(M_Z) = 0.126 \pm 0.025$$

$$\alpha_0(2 \text{ GeV}) = 0.3 \pm 0.3$$

- Uncertainty can be significantly reduced by considering newly generated JADE MC samples

$$\frac{\sigma_L}{\sigma_{\text{tot}}} = \left(\frac{\sigma_L}{\sigma_{\text{tot}}} \right)_{\text{PT}} + a_{\sigma_L} \cdot \frac{16\mathcal{M}}{3\pi^2} \frac{\mu_I}{\sqrt{s}} \cdot (\alpha_0(\mu_I) - \alpha_S(\mu) + \mathcal{O}(\alpha_S^2))$$

Particle Momentum Spectra

Test (soft) QCD predictions for hadron momentum spectra $x=2p/\sqrt{s}$, $\xi \equiv -\ln(x)$

Theoretical input

Next-to-Leading-Log Approximation (NLLA)
(coherence effects, angular ordering)

+

Local Parton Hadron Duality (LPHD)

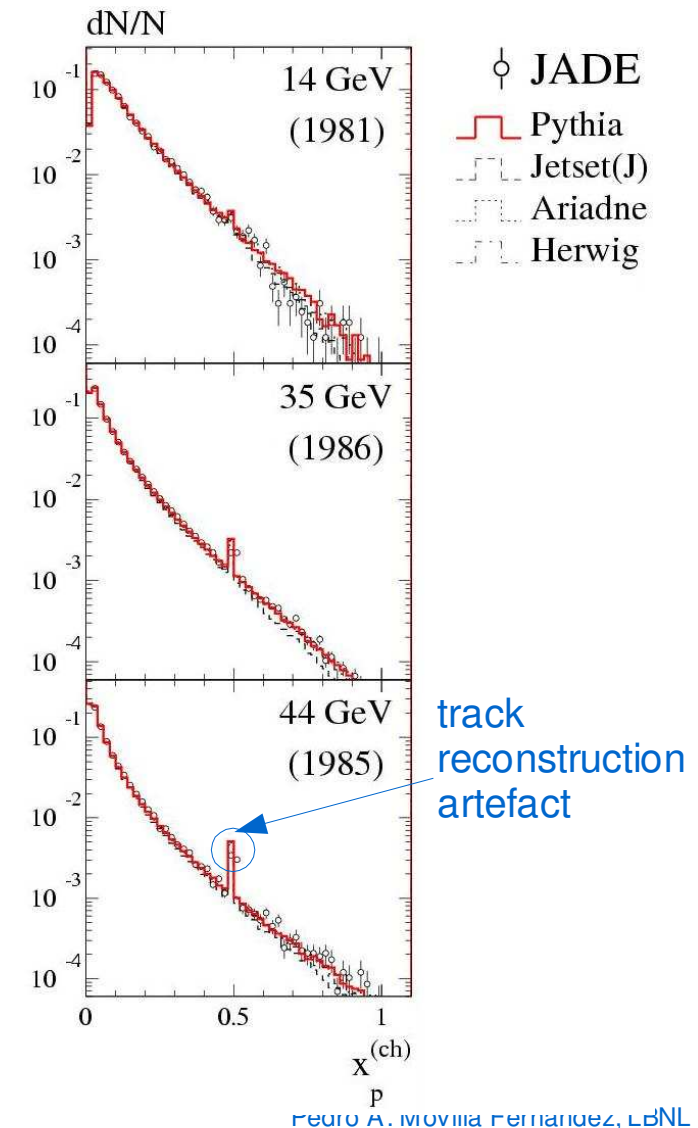
- properties of partons at the end of parton shower similar to those of hadrons
- hadronization **affects only normalization but not shape** of the spectra



Prediction

- shape around peak of ξ distribution
- \sqrt{s} dependence
- effects of heavy quarks

Uncorrected x spectra
(data vs. and detector MC)



Prediction for $\ln(1/x)$

Fong-Webber parametrization: skewed Gaussian

$$F_q(\xi, Y) = \frac{N(Y)}{\sigma\sqrt{2\pi}} \cdot \exp\left(\frac{k}{8} - \frac{s\delta}{2} - \frac{(2+k)\delta^2}{4} + \frac{s\delta^3}{6} + \frac{k\delta^4}{24}\right)$$

- includes soft gluon coherence effects
- spectrum is softer w/o coherence

$$\delta = (\xi - \langle \xi \rangle) / \sigma$$

$$\xi - \xi_0 \approx (11 + 2N_f) / (32 \cdot 9C_A)$$

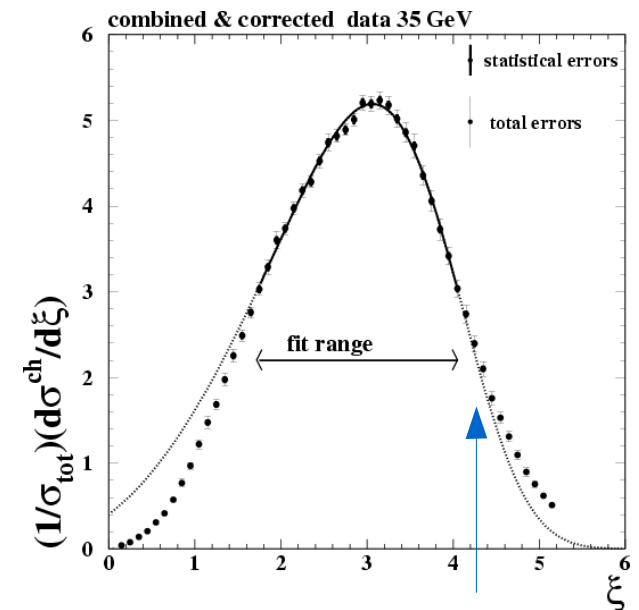
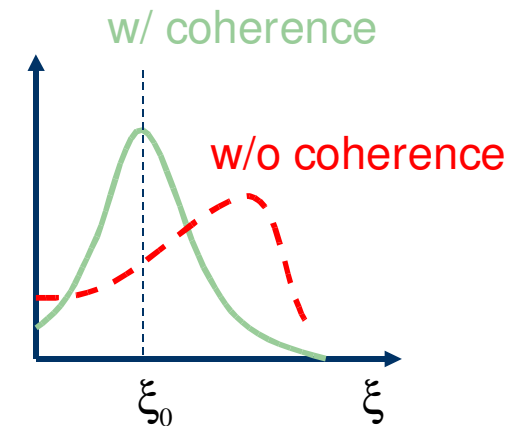
$$Y = \ln(\sqrt{s}/2\Lambda_{\text{eff}})$$

N = normalization factor related to chrgd multiplicity

$\langle \xi \rangle$: mean value
 ξ_0 : peak position
 σ : width
 s : skewness
 k : kurtosis

dependent
on Y and QCD
color factors

$$\langle \xi \rangle \equiv \langle \xi(Y) \rangle = \frac{Y}{2} \left(1 + \frac{\rho}{24} \sqrt{\frac{48}{\beta Y}} \right) \cdot \left[1 - \frac{\omega}{6Y} \right] + \mathcal{O}(1)$$



Test of Fong-Webber Predictions

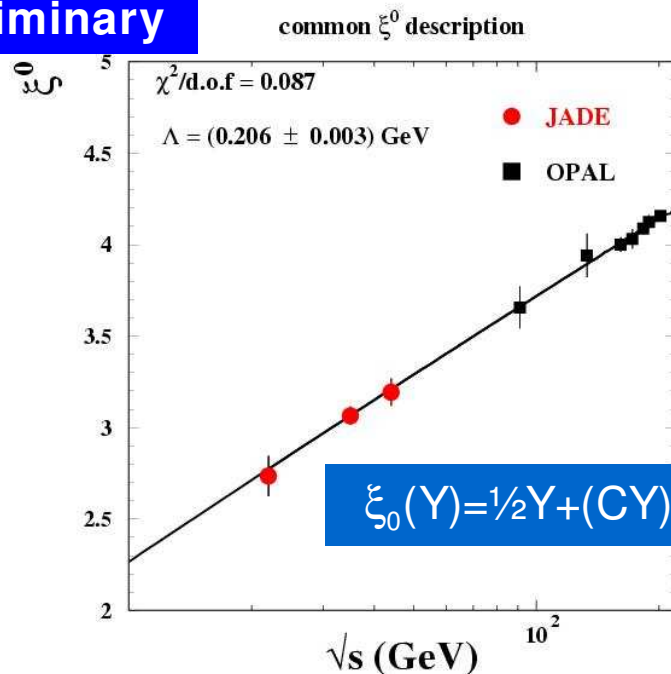
3 simultaneous fit variables:

$$\Lambda_{\text{eff}}, N \text{ and } \begin{cases} \langle \xi \rangle \\ \text{or } \xi_0 \\ \text{or } O(1) \end{cases}$$

Fong-Webber prediction

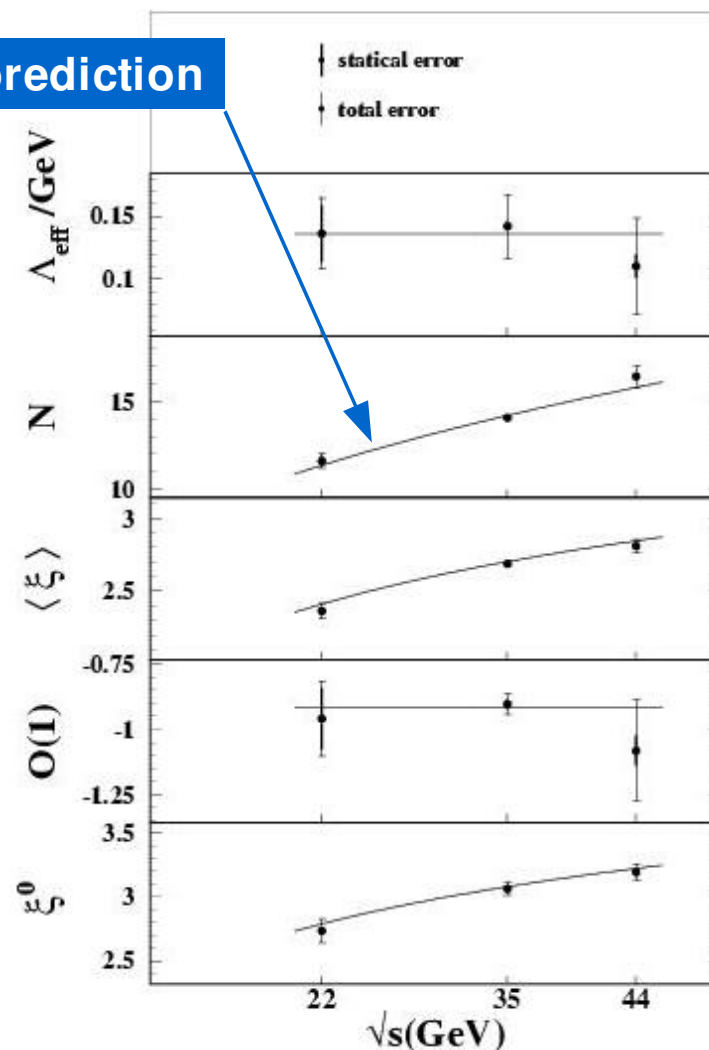
$\langle \xi \rangle$, ξ_0 and N depend on \sqrt{s} , Λ_{eff} and $O(1)$ constant

preliminary



$$\xi_0(Y) = \frac{1}{2}Y + (CY)^{1/2} + C + O(Y^{-1/2})$$

JADE PRELIMINARY

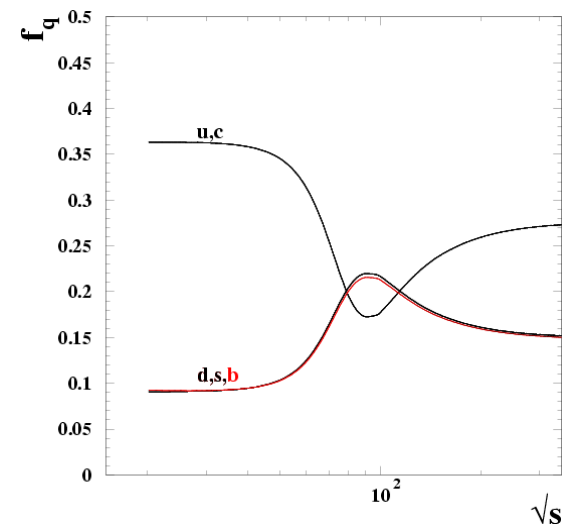


Good description of spectra & energy dependence

$$\Lambda_{\text{eff}} = 206 \pm 1^{\text{stat}} \pm 3^{\text{sys}} \text{ MeV}$$

Flavor Dependence

- write $\xi_0(\sqrt{s})$ as linear combination of peak positions $\xi_0^{(q)}(\sqrt{s})$ for flavour q , weighted with branching ratio $f_q(\sqrt{s})$
- $\xi_0^{(c,b)} - \xi_0^{(uds)} \propto 0.5 \ln(\Lambda^{(c,b)} / \Lambda^{(uds)})$
 \Rightarrow energy evolution is flavor dependent
- fix $\xi_0^{(uds)}, \xi_0^{(c)}, \xi_0^{(b)}$ with OPAL data @ $\sqrt{s} = M_Z$
- fit $\Lambda^{(uds)}, \Lambda^{(c)}, \Lambda^{(b)}$

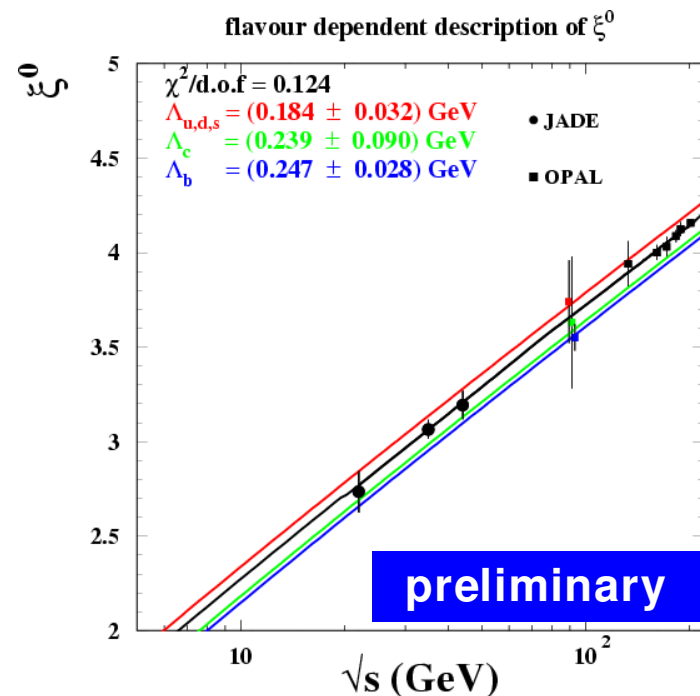


Mass effects about 20-30%

$$\Lambda^{(uds)} = 184 \pm 32 \text{ MeV}$$

$$\Lambda^{(c)} = 239 \pm 90 \text{ MeV}$$

$$\Lambda^{(b)} = 247 \pm 28 \text{ MeV}$$

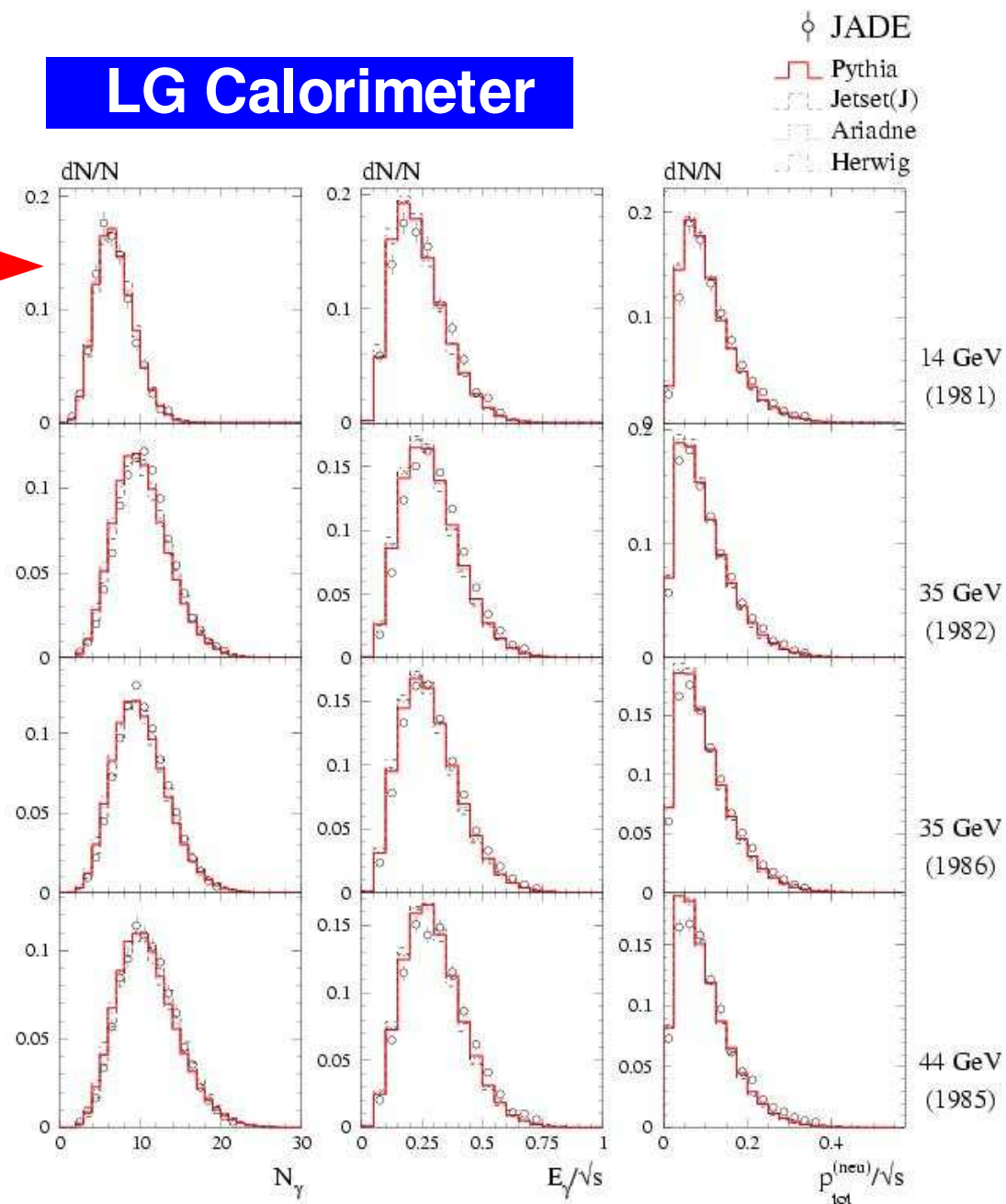


Performance

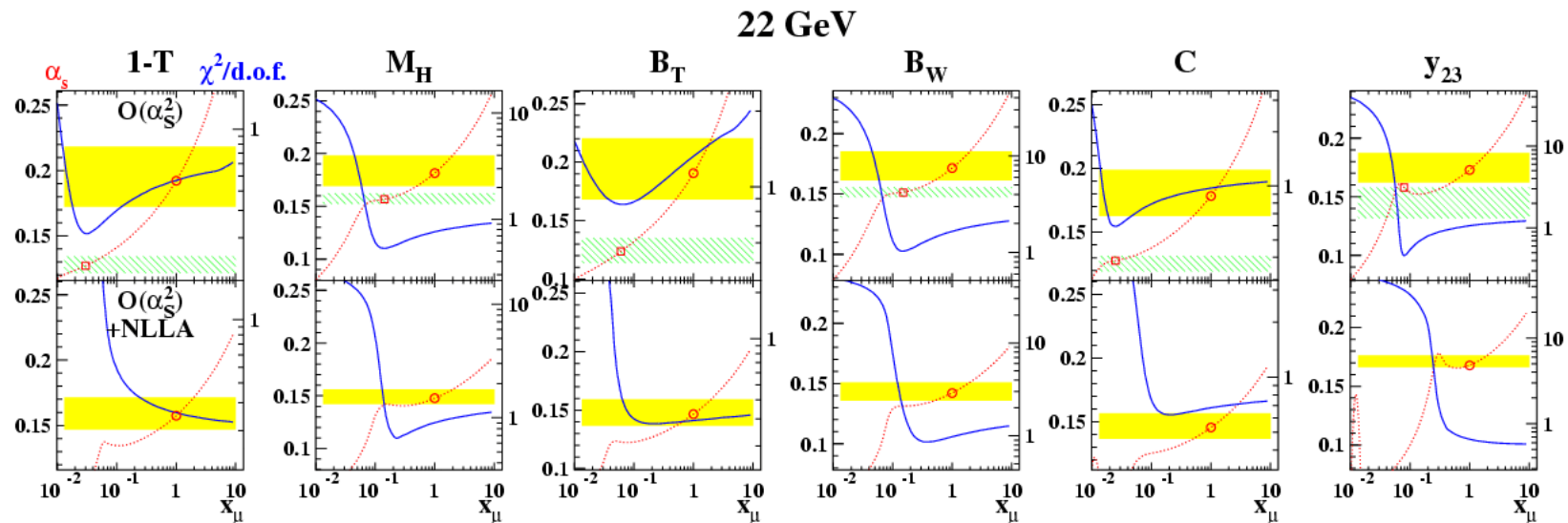
LG Calorimeter

Example:

$$N_\gamma, E_\gamma/\sqrt{s}, p_{\text{tot}}^{(\text{neu})}/\sqrt{s}$$



Renormalization Scale Dependence



- NLO+NLLA: reduced x_μ dependence around $x_\mu=1$ compared to NLO

- $\alpha_s(\sqrt{s}, x_\mu=1)$ more consistent than in NLO case
- But: sizable α_s dependence around $x_\mu=1$ still present

- Pure NLO: Preference for small $x_\mu^{(\text{opt})} = \mathcal{O}(0.01 \dots 0.5)$

- scale dependence around $x_\mu^{(\text{opt})}$ sometimes smaller, but...
 - less consistent individual results
 - (α_s, x_μ) fits not always stable, large statistical errors
 - no strong theoretical arguments for the choice $x_\mu = x_\mu^{(\text{opt})}$
- ⇒ have to consider **both** $\alpha_s(\sqrt{s}, x_\mu = x_\mu^{(\text{opt})})$ **and** $\alpha_s(\sqrt{s}, x_\mu=1)$

NLO+NLLA @ $x_\mu=1$ seems to be the “natural” choice